TIDE-LEVEL AND BOTTOM FRICTION EFFECTS ON
WAVE REFRACTION AS DETERMINED BY
NUMERICAL WAVE REFRACTION PROCEDURES

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TIDE-LEVEL AND BOTTOM-FRICTION EFFECTS

ON WAVE REFRACTION AS DETERMINED BY

NUMERICAL WAVE REFRACTION PROCEDURES

by

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ABSTRACT

Numerical wave refraction programs permit a detailed study of the
transformation of wave energy as waves move from deep water to shallow
water. By eliminating the subjectivity that is present with hand drawn
diagrams the effect of small variations in the initial assumptions and
wave conditions can be investigated. The effects on wave refraction of
tide level changes and bottom friction are investigated here. It is
demonstrated that a uniform increase in water level as would be caused
by tidal fluctuations can cause a significant change in the wave re-
fraction pattern for a given nearshore region. A computing procedure
is developed to permit numerical refraction programs to account for
bottom friction. The reduction in wave height caused by bottom friction
depends primarily on bottom slope; this relation is shown in tabular
and graphical form.

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TABLE OF SYMBOLS

A   approach angle of wave ray

β ray separation in shallow water divided by ray separation in deep water

C   wave velocity

C_o deep water wave velocity

f   dimensionless friction coefficient for the bottom.

FK   curvature of ray

g   acceleration due to gravity

H   wave height at position x

H_o deep water wave height

H_1 wave height at position x_1

H/H_o wave height at position x divided by deep water wave height

HHFR   wave height at position x, when bottom friction is included, divided by deep water wave height

K_f wave height reduction factor due to bottom friction alone

K_r refraction factor

K_{fr} combined friction and refraction factor

K_s direct shoaling factor

L   wave length

L_o deep water wave length

s   wave ray

T   wave period

x   distance measured along the wave ray in the direction of propogation of the waves

Δx $x - x_1$

π 3.1416...

Note: All values are assumed to be in the English System of Units.

1. Introduction

Preparing accurate wave refraction diagrams is a necessary first step in many coastal engineering and amphibious operations. The advent of the numerical wave refraction programs [Griswold (1963), Stouppe (1966), Wilson (1966)] has considerably reduced the time required to construct a wave refraction diagram. The speed of the computer operations permits more parameters to be included in the calculations and improves the accuracy of the output. Of equal importance is the fact that numerical products provide a completely objective basis for evaluating the cumulative effect of various assumptions on wave refraction.

The present study has investigated the effects of tide-level changes and bottom friction on wave-refraction patterns for several environments. The investigation first compared the wave refraction programs of Griswold (1963), Stouppe (1966), and Wilson (1966). Since there was no way available to the author to compare program accuracy on an absolute scale, the comparison was based on method of computation, simplicity of use, and presentation of results.

The program written by Stouppe was considered to have the most potential and was chosen for use in this investigation. The major advantages of Stouppe's program are these:

(1) The program uses water depth directly as the interpolation surface for evaluation of wave speed, thereby limiting the number of computations and increasing the program versatility.

(2) The program uses a second-order non-linear differential equation to determine the refraction coefficient at each point along the ray. Thus, the wave height at each point can be computed.

(3) The program uses constant time steps in the computation rather than constant distance steps. This reduces the distance between computations as the shoreline is approached. Thus for the same number of computer operations a greater percentage of computations are in the shallowest area where refraction, friction, etc., are most important, and are changing rapidly.

(4) The program includes a graphical output that plots the wave orthogonals, wavecrests and the shoreline.

The following modifications were made to Stouppe's program:

(1) The program was made to recycle, permitting more effective use of computer time when more than one diagram is to be constructed.

(2) Provision was made to add a constant value to the depth field to investigate tide level effects.

(3) A subroutine was added to account for bottom friction in the computation of wave height.

2. Computer Program.

Depth grid.

The first step in the utilization of this program is the construction of a grid of water-depth values for the desired area. The grid must be sufficiently large so that the starting point of all rays to be followed is in deep water, i.e., the ratio of water depth to deep water wave length (d/L_o) is greater than 0.5. By convention the x-axis is positive increasing toward the shore while the y-axis is positive to the left of the x-axis. The grid interval is selected so that the bottom contours are reasonably parallel to one another within a given square.

In constructing the depth grid it is advantageous to record the average value of all depths within that grid square, rather than the value of water depth at the intersection point. This procedure tends to correct for small variations in the depth of water within the depth grid without necessitating the use of a smaller grid size. All actual depths are made positive; extrapolated depth values are continued on land for two grid units from the shoreline and are made negative. Beyond two grid units from the shoreline any arbitrary negative depth may be used. For depths on the shoreline itself zero is used.

To reduce the time required to obtain the depth grid a clear plastic overlay with a black dot at each grid intersection point was prepared by initially locating the grid dots on white paper and producing a viewfoil transparency with an Ozalid copier, Model 400.

Input data.

Stouppe's order of data input was modified to permit the program to recycle. The present data deck consists of three sections. The first section contains only the value of MM and NN which designate the number of points in the depth grid in the x and y directions respectively. The

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second section contains the water depth grid. These values are arranged so that the computer reads all the y values for each successive x-grid position. Water depths are read in fathoms and are converted to feet within the computer program. The last section contains one card for each set of input parameters for which it is required to construct a wave refraction diagram. The input parameters include:

X,Y: The grid position for the starting point of the first ray (feet). All starting rays must be more than two grid intervals in distance from the edge of the depth grid.

FCF: The coefficient of bottom friction.

TIDE: The tide level, in feet, above chart depth for which computation is required. This value is subtracted from the depth grid after each refraction pattern is completed.

HINT: The deep water wave height (feet). This is required for the friction subroutine.

T: The initial wave period (seconds).

A1:   The initial wave angle (degrees). The smaller angle measured between the positive Y direction and the initial wave crest. The angle is made negative if the slope of the wave crest is negative.

NOR: The number of rays to be followed.

TIME: The time interval between computations for advancing of the wave front (seconds).

DIST: The distance between rays (feet).

GRID: The grid interval (feet).

This order of data input permits wave refraction diagrams to be computed for many combinations of input variables while requiring the computer to assemble the program and read the depth field only once.

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Computer output.

The output from the computer consists of both a printed output and a graphical output. The printed output variables are these:

X,Y: The x and y coordinates for a given wave crest and ray number (yards).

COREFR: The coefficient of refraction (K_r) for the wave at the point x,y.

HHO: The ratio of wave height to deep water wave height neglecting bottom friction.

HHFR: The ratio of wave height to deep water wave height when bottom friction is included.

NGO: Indicates that the ray has terminated (1), or it is continuing (2).

DEPTH: The water depth for grid position X and Y (feet).

The graphical plot of wave crests is programmed for the Calcomp 160 system utilizing the DRAW subroutine programmed by J. R. Ward for the Fortran 60 system. See Appendix II, Stouppe (1966), for subroutine listing. The first and each succeeding third wave crest are plotted. The zero water depth points are used for contouring the shoreline on the graph.

Appendix 2 contains a sample of the printed and graphical output for Monterey Bay, California.

Computer operations.

Since the details of the computer operations are discussed by Stouppe (1966), only the main features will be discussed here. The formulas used in the computations are listed in Appendix 3.

The water depth at the first point is computed by fitting the closest nine grid-point depths to a quadric surface by the least-squares method. An iterative procedure is then used to solve for wave velocity. It is assumed here that wave velocity is a function of water depth and period only.

The wave ray is then moved to the next point by solving for the ray curvature and projecting the ray forward a distance equal to the product of the wave speed for the point multiplied by TIME. At this new point the value of ray separation (β), coefficient of refraction (K_r), shoaling factor (K_s), H/H_o, and HHFR are calculated.

This procedure is repeated until all orthogonals have been advanced one time interval. The new wave crest is plotted and the entire procedure is repeated until all orthogonals have either gone off the grid or reached the shoreline.

3. The Effects of Tide Level Changes on Wave Refraction Patterns.
Differences in shoaling factor, wave speed, and ray curvature at specific
depths.

The effect on wave refraction of a uniform increase in water depth
caused by tide level changes is cumulative and is dependent on the bottom
depth contours. Therefore, to evaluate the effect properly, a wave ray
must be followed along its entire distance from deep water to the shore.
However, by calculating the value of shoaling factor (K_S), wave speed (C),
and ray curvature (FK) at both high tide and low tide it is possible to
evaluate the order of magnitude of the differences in the basic parameters
of wave refraction caused by tide level fluctuations.

The value of K_S, C, and FK were calculated initially for 25, 50,
and 100 foot water depths; second calculations were made for a water
depth equal to the initial water depth plus a tide level increase of
6, 10, and 16 feet. To evaluate these differences on a relative scale
a percent difference was calculated by using the formula:

$$\% \text{ difference X} = \left| \frac{X_{HT} - X_{LT}}{X_{HT}} \right| \qquad (1)$$

where

X = variable representing C, K_S, or FK

X_{ht} = value of X at high tide water depth

X_{lt} = value of X at low tide water depth.

The percent difference of K_S was generally small and under certain
conditions went to zero (for those values associated with the inflection
point in the curve when K_S is plotted against water depth).

Figure 1 shows the percent difference in wave speed corresponding
to the low tide water depth for a specific tide range and wave period.

Figure 1. EFFECT ON WAVE SPEED OF VARYING TIDE LEVELS FOR 8-16 SECOND WAVES.

8 Sec. Waves

12 Sec. Waves

16 Sec. Waves

PERCENT DIFFERENCE

WATER DEPTH (LOW TIDE)

TIDE RANGE:　　- - - - 6 Ft.　　- · - · - 10 Ft.　　———— 16 Ft.
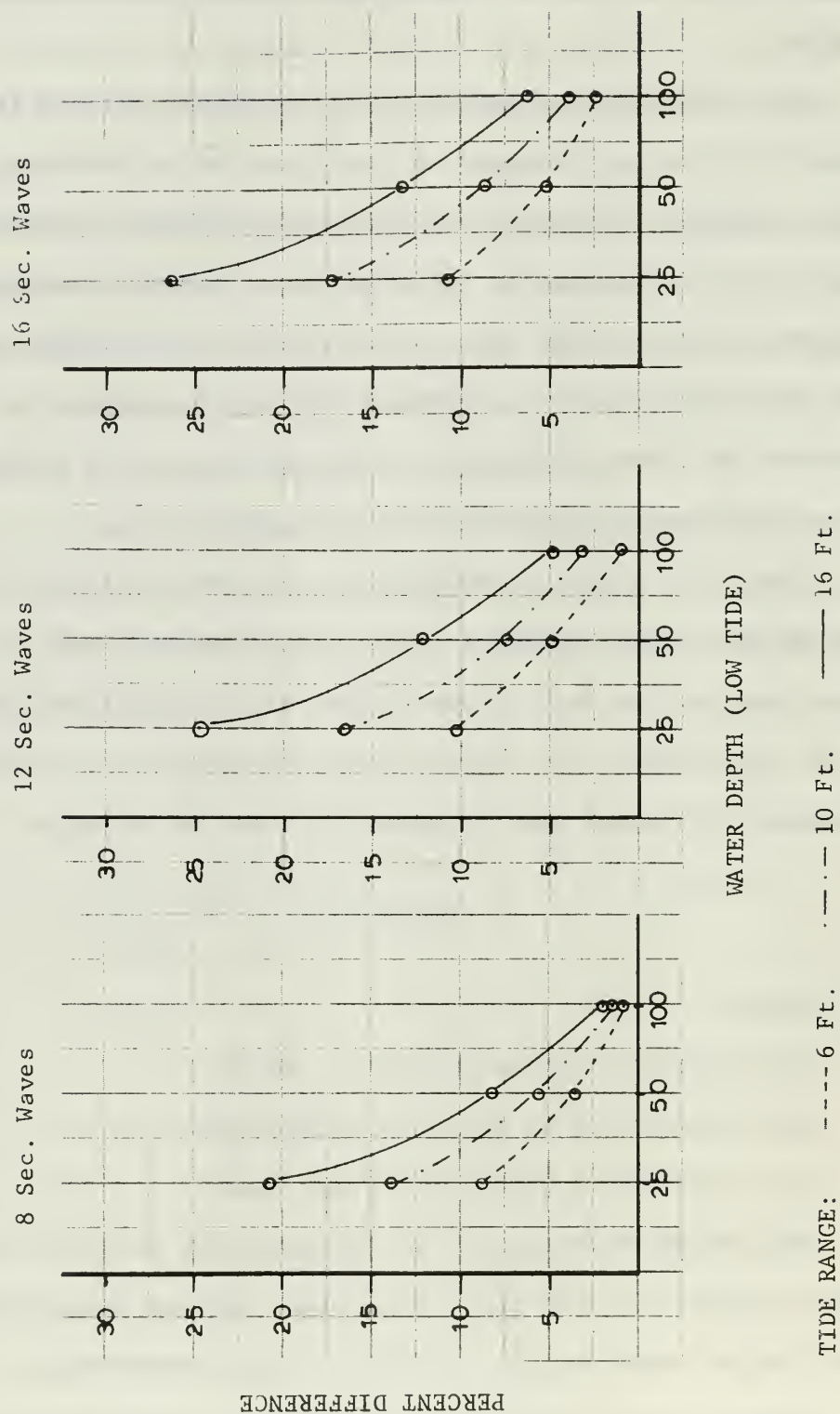
It is apparent that the difference is often greater than 10 percent and increases with increasing wave period, increasing tide range and decreasing low tide water depth.

The values of ray curvature (FK) were determined using the equation:

$$FK = \frac{1}{c}\left[\sin A \frac{\partial c}{\partial x} - \cos A \frac{\partial c}{\partial y}\right] \qquad (2)$$

where

$\qquad$ A = approach angle

$\frac{\partial c}{\partial x}, \frac{\partial c}{\partial y}$ = derivative of wave speed in the X and Y directions respectively.

Figure 2 shows the percent difference in FK versus tide range (computed using equation (2) with the following initial values: A = 30°, $\frac{\partial c}{\partial y} = 0$, $\frac{\partial c}{\partial x} = \Delta C$ for a twenty foot change in water depth starting with an initial depth of 100 feet). The values of percent difference plotted are representative of the percent difference for all values of A, $\frac{\partial c}{\partial x}$, $\frac{\partial c}{\partial y}$, and water depth; this occurs because the terms inside the brackets in equation (2) have nearly the same value for high tide and low tide and tend to cancel out in the percent difference calculation. This reduces the percent difference calculation for FK to

$$\% \text{ difference FK} = \left| \frac{C_{LT} - C_{HT}}{C_{HT}} \right| \qquad (3)$$

The fact that the difference calculation is primarily dependent on tide range and wave speed is clearly shown in Figure 2.

It is concluded that the change between high tide and low tide in a refraction pattern is primarily determined by the change in ray curvature (FK).

Figure 2. EFFECT ON RAY CURVATURE OF VARYING TIDE LEVELS FOR 8-16 SECOND WAVES
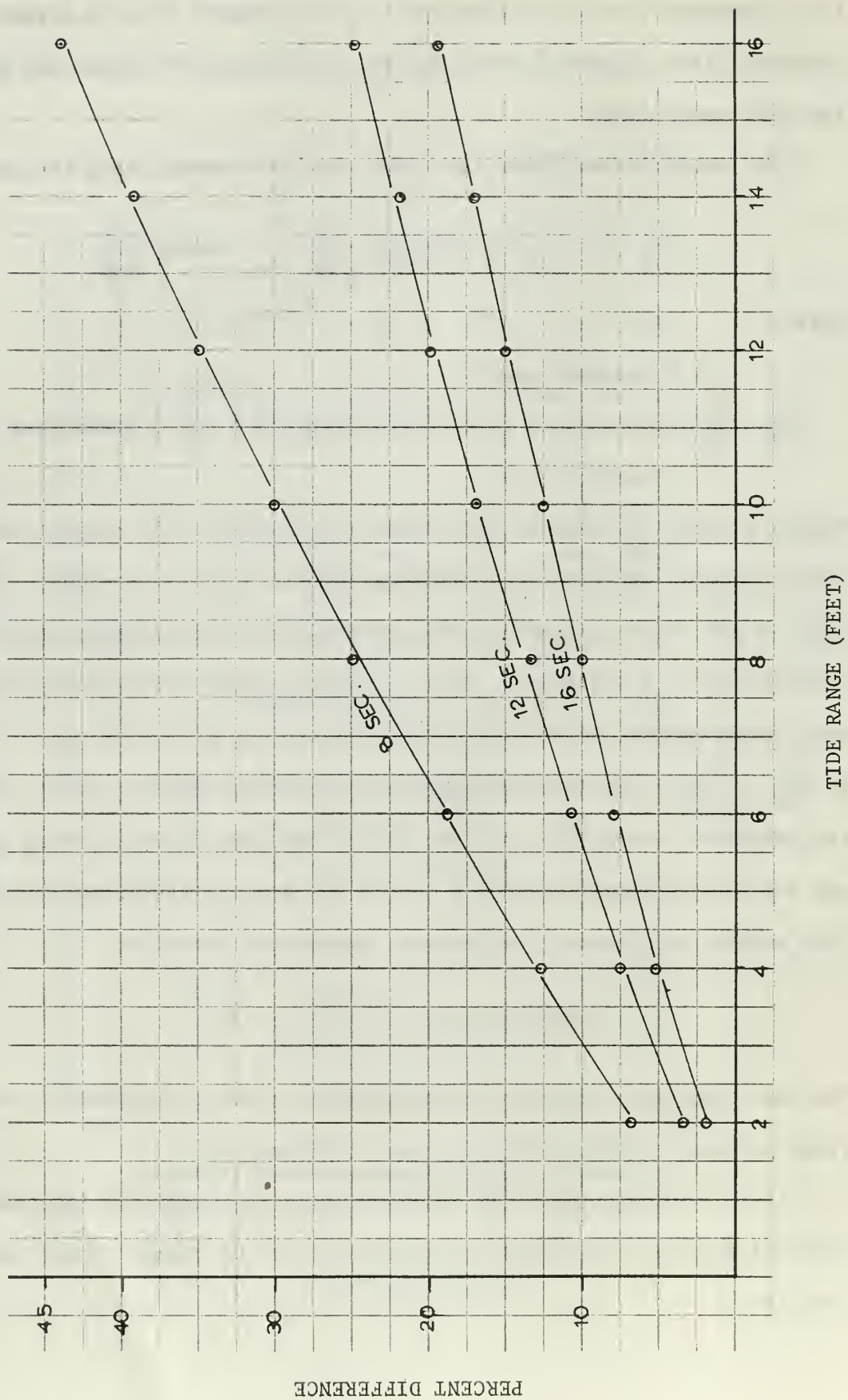
<u>Difference in wave refraction patterns for specific locations</u>.

To investigate the combined effect of the changes in C, K_s and FK caused by a uniform increase in water depth, wave refraction diagrams were constructed for several locations using both the low tide water depths and the high tide water depths.

The first area considered was the California coast near Big Sur, between latitude 36° 14' 30" and latitude 36° 17' 42". This area was chosen because eight-second waves arriving on the coast will be refracted by the offshore bar (shown by the shaded area in Figures 3 and 4) at low tide but not at high tide.. Thus tide level changes will cause selective refraction by the offshore bar. Figure 3 shows the refraction pattern for 8 second waves approaching from 270 degrees at low tide; Figure 4 shows a different pattern for the same condition at high tide.[1]

Figures 3 and 4 show two major differences in the refraction pattern. First, orthogonals 6 and 7 cross approximately halfway to shore at low tide but they do not cross at high tide.[2] Secondly, at low tide there is a convergence of wave orthogonals at Point A; this convergence is not present at high tide.

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[1]To make the changes in the orthogonal pattern more prominent Figures 3-8 are plotted with an expanded ordinate scale. Also, the computer was not used to contour the wave crests but rather the wave orthogonals were contoured manually; the shoreline was indicated by a triangle plotted whenever water depth was zero. TIME equalled 30 seconds for all diagrams.

[2]Interpretation of the effect of crossed orthogonals is beyond the scope of this paper. In this discussion we will only be concerned with the difference in ray paths between low tide and high tide.

Table 1 shows the value of the wave-height ratio (H/H_o) computed at four wave crests before the shoreline is reached for specific points along the coast. This table clearly shows that the value of wave height can be considerably different at low tide and high tide.

Figures 5 and 6 represent the same initial conditions as Figures 3 and 4 except that the initial wave direction is from 310 degrees. The change in the orthogonal pattern is clear. It is noted that in Figures 3 and 4 the primary change in the orthogonal pattern (between low tide and high tide) is in the vicinity of points B and C, whereas in Figures 5 and 6 the greater change occurs near Point A.

Wave refraction diagrams were also computed for the coast of Maine between latitude 44° 39' 35" and latitude 44° 44' 45". This area was chosen in order to determine if the combination of a large tide range (16 feet) and deep water depths (greater than 200 feet a short distance from the shoreline) would cause a change in the refraction pattern. Figures 7 and 8 show the refraction patterns for 16-second waves arriving from 070 degrees at low tide and high tide. The difference in refraction patterns is evident. Table 3 shows the H/H_o ratios (calculated at four wave crests before reaching the shoreline) for specific locations at low-tide and high-tide conditions.

In total, about 20 sets of refraction patterns were analyzed and it appears impossible to predict what changes in wave height and refraction patterns will occur as the result of tide level changes. The only generalization that can be made is that the curvature of an orthogonal is generally greater at low tide than at high tide. It is concluded that precise water-level information, including tide state, should be incorporated into wave refraction procedures.

TABLE I

H/H_o RATIO AT LOW TIDE AND HIGH TIDE FOR SPECIFIC COASTAL LOCATIONS
NEAR POINT SUR, CALIFORNIA.

| LOCATION | H/H_o RATIO | |
(SEE FIG. 3)	LOW TIDE	HIGH TIDE
A	1.1	1.2
B	1.3	.9
C	3.1	1.7
D	.8	.8

TABLE II

H/H_o RATIO AT LOW TIDE AND HIGH TIDE FOR SPECIFIC COASTAL LOCATIONS
NEAR EASTERN HEAD, MAINE.

| LOCATION | H/H_o RATIO | |
(SEE FIG. 7)	LOW TIDE	HIGH TIDE
A	2.8	3.3
B	1.0	1.2
C	.7	.8
D	.7	.7
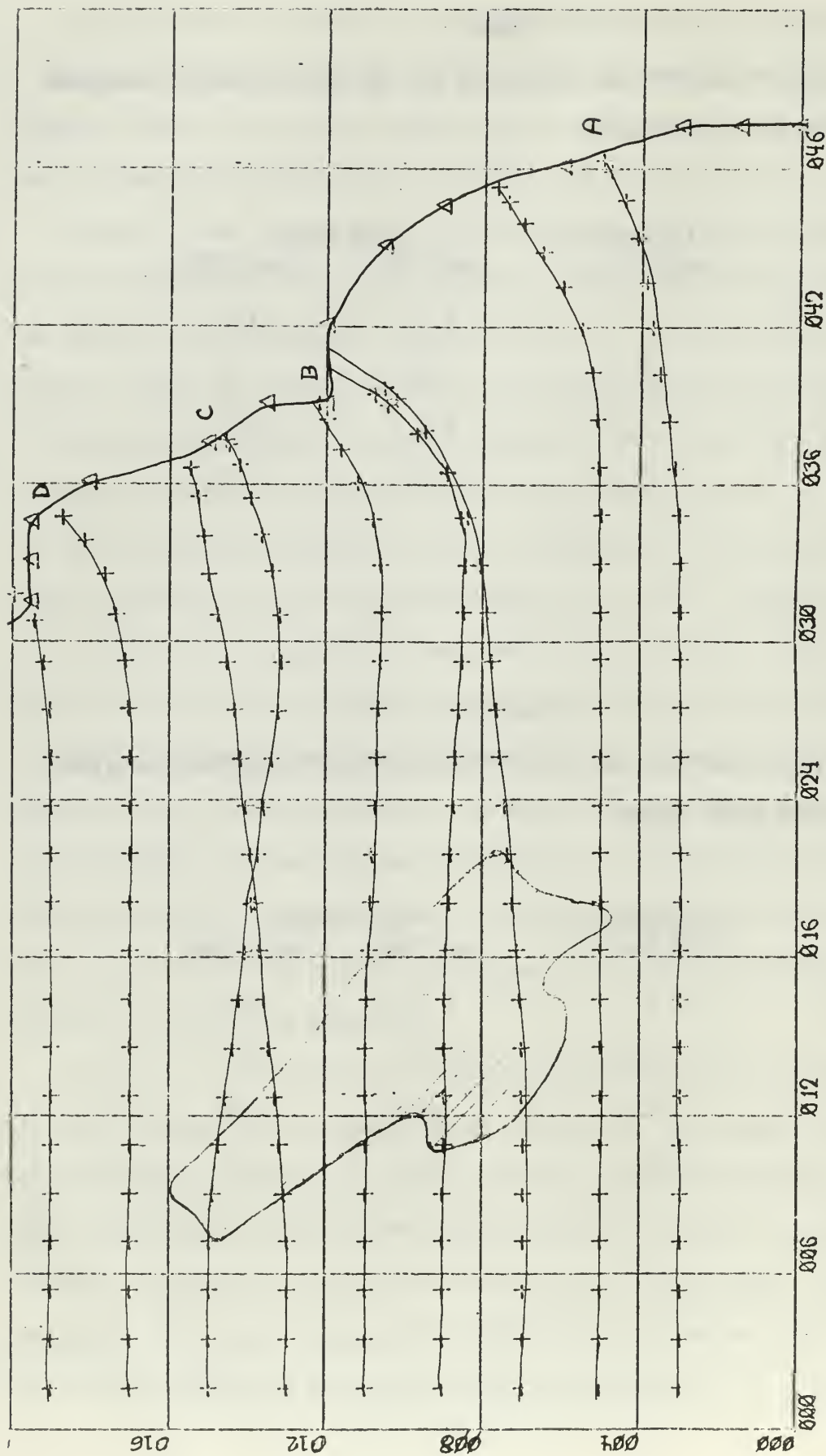
Figure 3. Low tide refraction diagram for Big Sur, California. T = 8 sec. A = 270°. TIME = 30 sec. Latitude 36°14'30" to latitude 36°17'42". East-West Scale 6000 Ft./inch. North-South scale 4000 Ft./inch.

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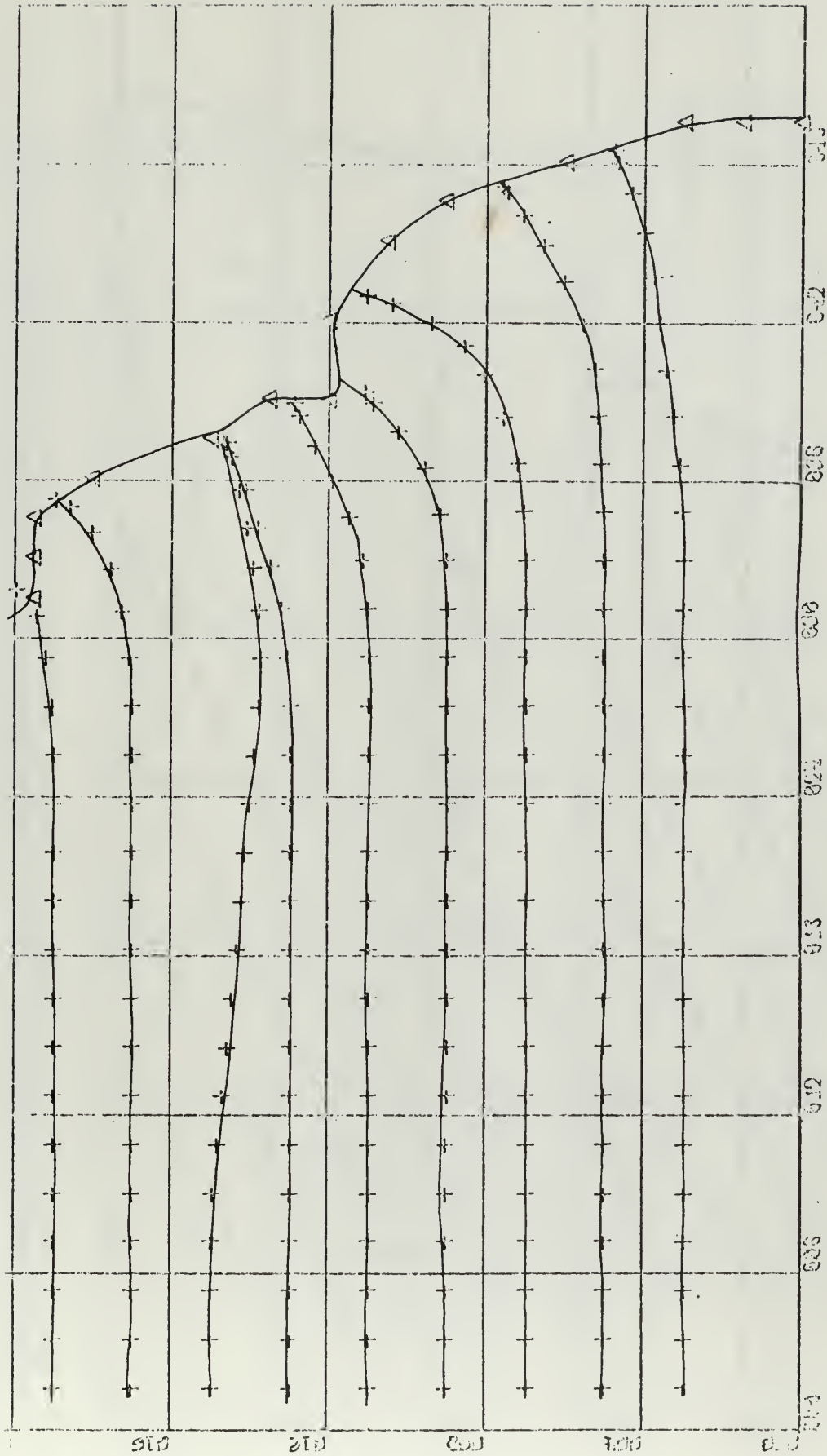
Figure 4. High tide refraction diagram for Big Sur, California. T = 8 sec. A = 270°. TIME = 30 sec. Latitude 36°14'30" to 36°17'42". East-West scale 6000 Ft./inch. North-South scale 4000 Ft./inch.
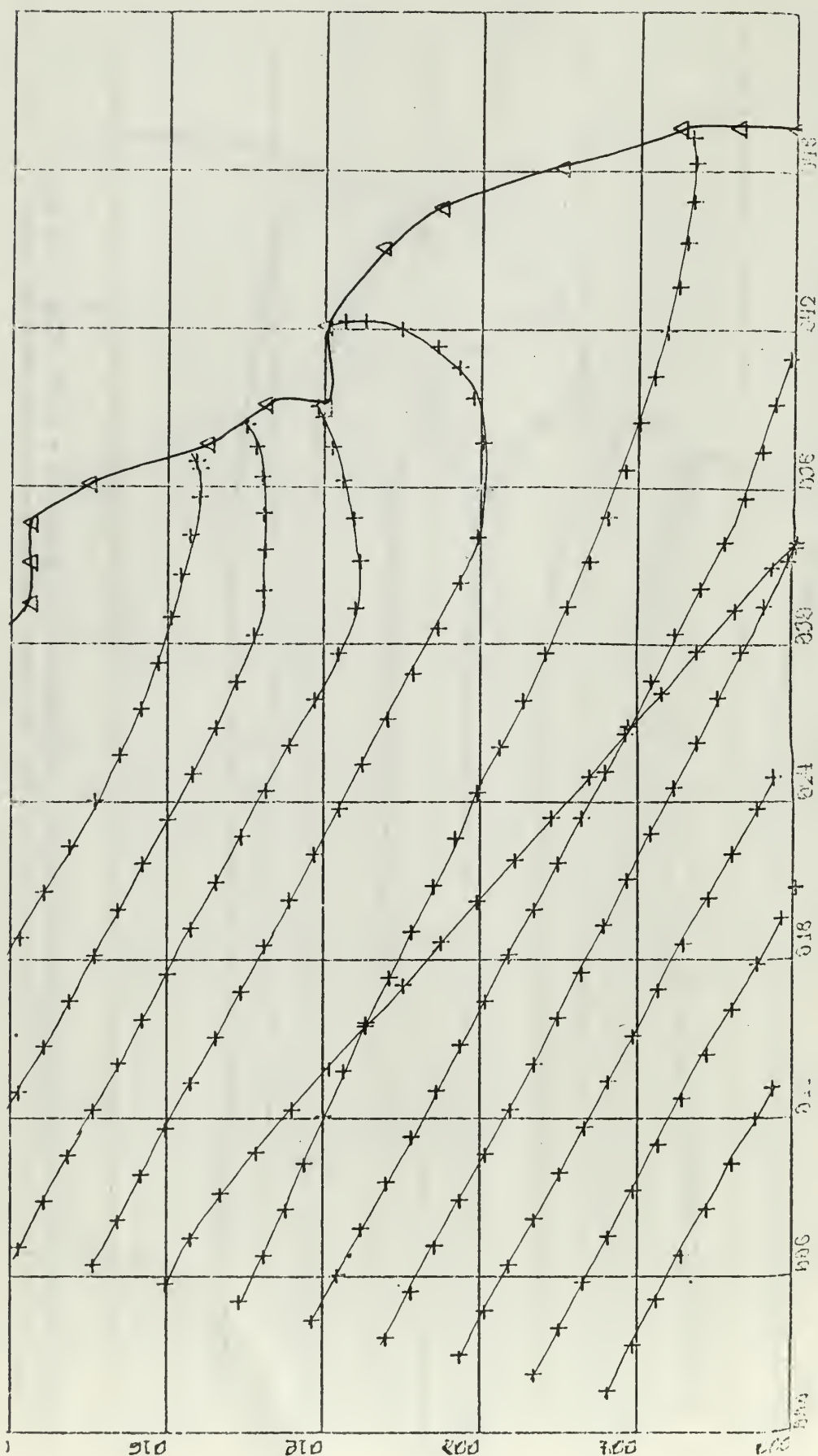
Figure 5. Low tide refraction diagram for Big Sur, California. T = 8 sec. A = 310°. TIME = 30 sec. Latitude 36°14'30" to 36°17'42". East-West scale 6000 Ft./inch. North-South scale 4000 Ft./inch.

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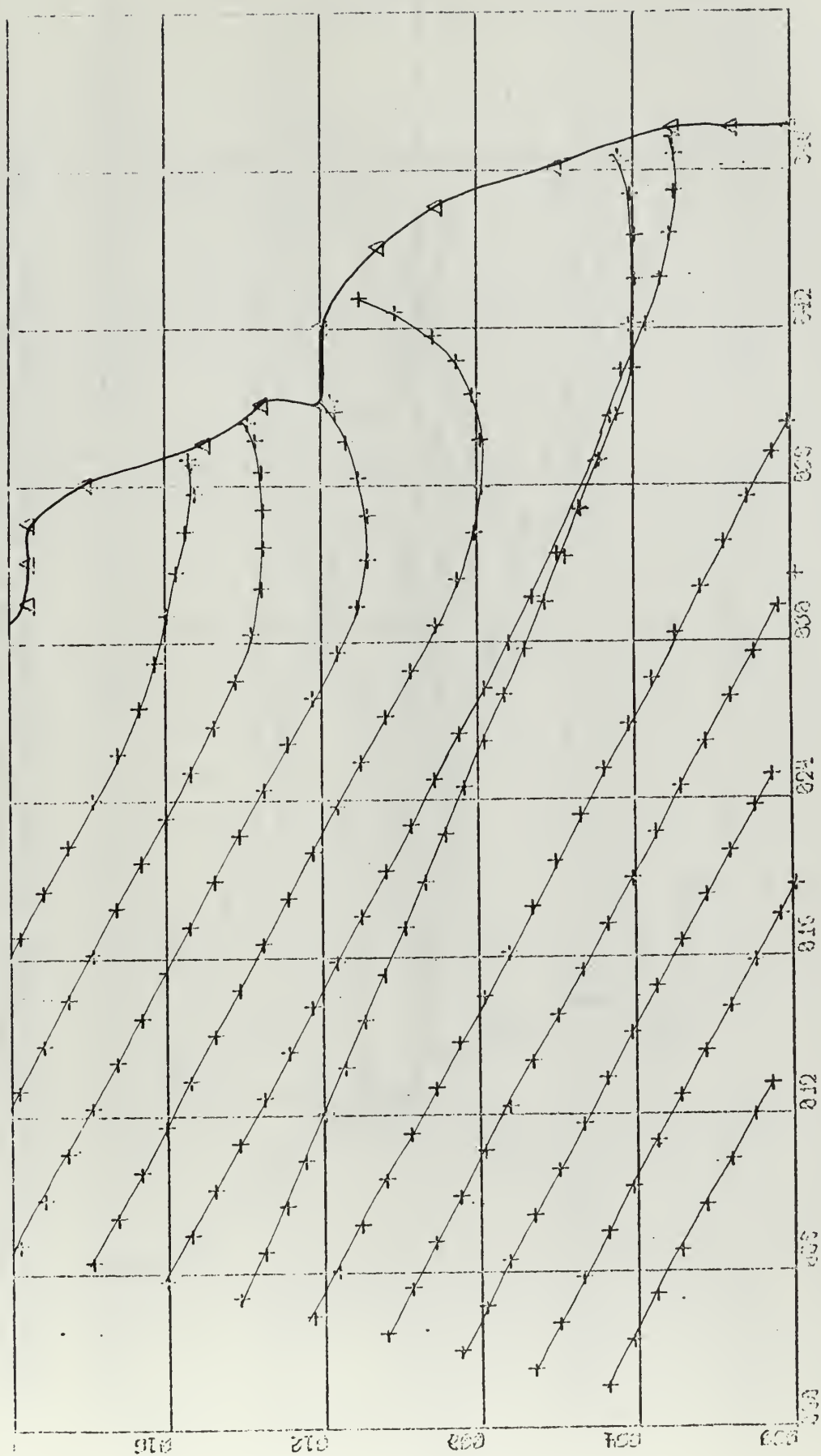
Figure 6. High tide refraction diagram for Big Sur, California. T = 8 sec. A = 310°. TIME = 30 sec. Latitude 36°14'30" to latitude 36°17'42". East-West scale 6000 Ft./inch. North-South scale 4000 Ft./inch.
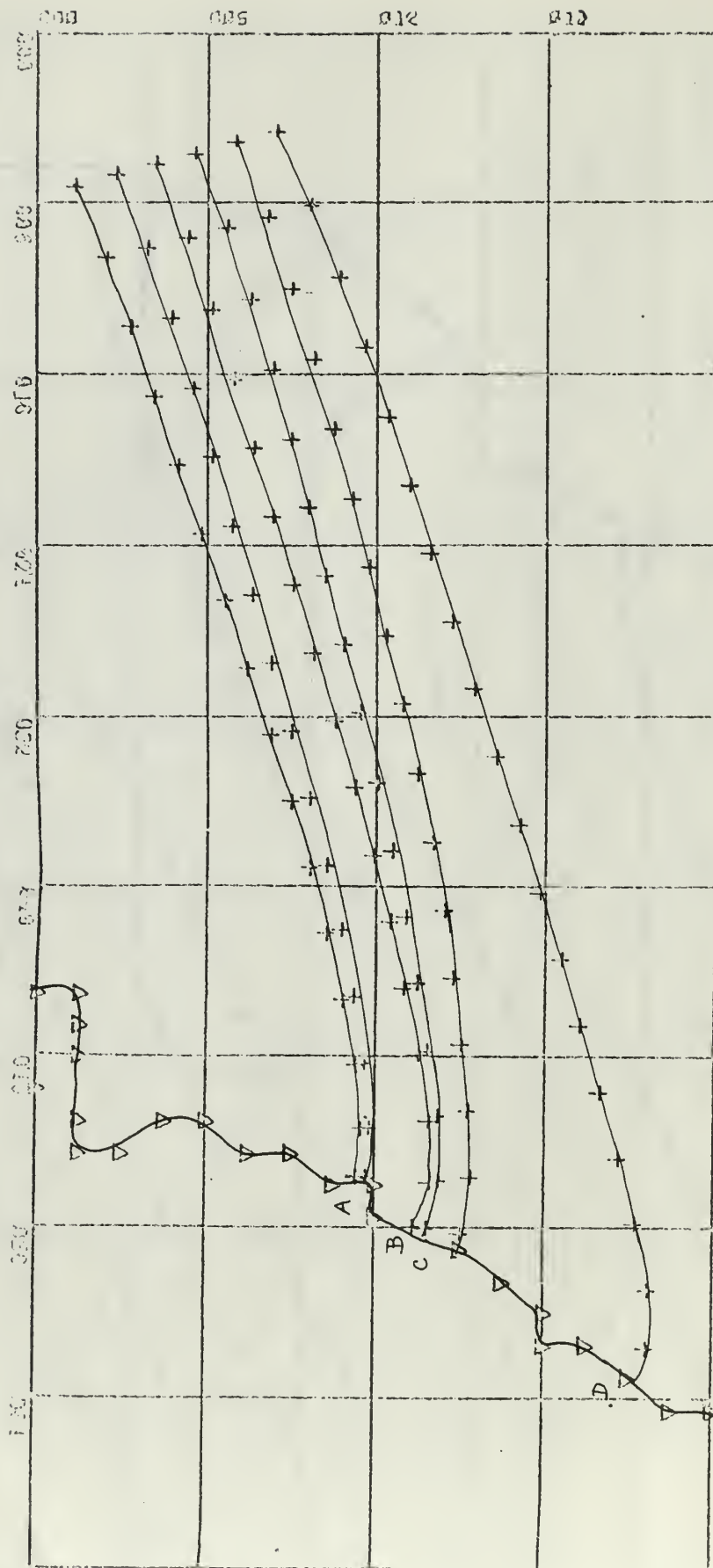
Figure 7. Low tide refraction diagram for Eastern Head, Maine. T = 16 sec. A = 070°. TIME = 30 sec. Latitude 44°39'35" to latitude 44°44'45". East-West scale 8000 Ft./inch. North-South scale 6000 Ft./inch.
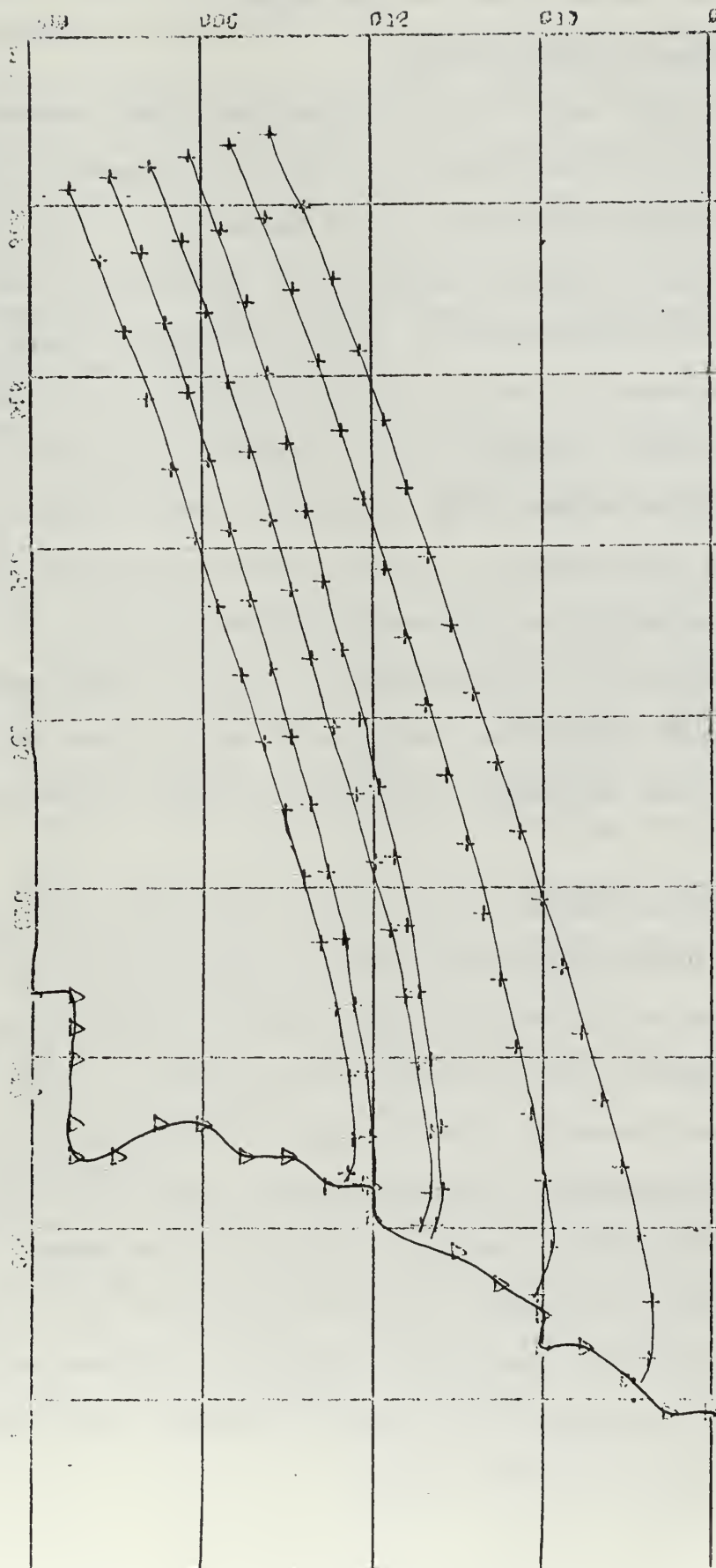
Figure 8. High tide refraction diagram for Eastern Head, Maine. T = 16 sec. A = 070°. TIME = 30 sec.
Latitude 44°39'35" to latitude 44°44'45". East-West scale 8000 Ft./inch. North-South scale 6000 Ft./inch.

4. Bottom Friction Effects on Wave Height.

Introduction to bottom friction.

     The present method for calculating wave height assumes that the propagation of energy between two adjacent orthogonals is conserved as the wave proceeds from deep water to shallow water. This implies that the addition of energy by surface winds, dissipation of energy by bottom friction or internal friction, and the reflection of energy by a steep slope are absent. In nature this is not the case - the wave energy between adjacent orthogonals may be changed by all of these means.

     According to Lamb (1932), in fluids of small viscosity (such as sea water), the velocity of the wave and the relationship between depth, length, and period are unaltered by internal friction. This is based on the assumption of a sinusoidal wave form but the result appears to indicate a very slow rate of damping of all waves in deep water, which is in accord with the limited observations in nature (Putnam and Johnson, 1949).

     At the sea bottom, however, friction can cause a loss of wave energy. It can be demonstrated both theoretically and experimentally that the particle velocities of shallow water waves are finite at the bottom and actually approach the theoretical orbital values at a short distance from the bottom. Therefore, a boundary layer in which mechanical energy is dissipated through the distortion of fluid elements must exist at the bottom. The effective roughness of a sandy bottom probably is determined by the size of the ripples in the sand rather than by the size of the sand grains. The ripple size, however, appears to be determined by the size and sorting coefficients of the sand in addition to the height and period of the wave and the depth of water.

Putnam and Johnson established the general magnitude for the dimen-sionless friction coefficient for the sea bottom to be 0.01. (This value was computed assuming initial conditions of 12 second waves, 4 feet high, traveling over a sandy beach with a ripple spacing of 5 inches.) Putnam and Johnson point out that since the friction factor only enters the equations for wave height to the first power, the friction factor could change by $\pm$ 50 percent without appreciably changing the order of magnitude of wave-height reduction.

Based on the following assumptions Putnam and Johnson were able to develop a procedure to calculate wave height when bottom friction is included.

(1) The oscillatory motion at the bottom is sinusoidal and corresponds to the wave theory based on small amplitudes.

(2) The friction coefficient does not vary with velocity and is approximately independent of water depth. This assumption amounts to choosing an average friction factor for the entire region over which the sea bottom affects the wave motion.

(3) Perpendicular flow at the bottom resulting from percolation in the bottom material is negligibly small.

(4) The sea bottom has a constant upward slope from offshore to the breaker point.

Computing procedures.

Bretschneider and Reid (1954) extended the original work of Putnam and Johnson and developed new equations to solve for wave height which included simplified equations for the special cases of constant water depth and constant bottom slope.

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Bottom friction is of importance only on gently sloping beaches and in shallow water; thus it is possible, when using numerical wave refraction procedures, to calculate the reduction to wave height due to bottom friction by making the assumption that the water depth is constant between successive computations along the ray path from deep water to the shoreline.

The wave height at each step is computed by the equation

$$H = H_1 \left[1 - \left\{ (1 - K_{f_1}) + (1 - K_{f_2}) + \cdots + (1 - K_{f_m}) \right\} \right] \quad (4)$$

where

   H_1 = the calculated wave height, neglecting bottom friction, for
         the point;

   K_{f_n} = the refraction factor between point n-1 and n.

The coefficient of friction (K_f) is calculated by the equation (from Bretschneider and Reid)

$$K_f = \frac{1}{\dfrac{A' \phi_f}{K_s} \Delta \alpha + 1} \quad ; \quad (5)$$

$$A' = \frac{f H_1}{T^4} \quad ;$$

$$\phi_f = \frac{64 \pi^3}{3 g^2} \left(\frac{K_s}{\sinh \dfrac{2 \pi d}{L}} \right)^3 \quad ;$$

   K_s = direct shoaling factor;

   $\Delta \alpha$ = incremented distance.

K_f is computed at each ray point with Δx equal to the distance along the wave ray between point n and n + 1. It is assumed in the computations that the water depth between point n and n + 1 is constant and equal to the depth at point n.

Results of bottom friction computations.

The accuracy of the approximation that water depth is constant can be seen by a comparison of wave height obtained by this procedure to the wave height obtained by the more sophisticated and accurate procedure used by Putnam and Johnson. This comparison is shown in Table 3 (computed for wave period = 12 seconds, bottom slope = 5 feet). The comparison is very favorable along the entire distance of travel from the point that the wave first feels bottom to the breaking point. The difference is certainly within the order of magnitude of the error introduced by other assumptions. The difference in values is caused by the approximation to constant depth steps in the calculating procedure.

Since this program uses constant time steps in moving each ray point toward the shoreline, the horizontal distance over which depth is assumed constant can be reduced by shortening the computing time interval (TIME). Table 4 shows the reduction (in percent) of wave height at the breaking point for different computing time intervals (with wave and bottom conditions the same as shown for Table 3 above). As expected, there is a slight increase in wave height reduction as the computing interval is decreased. It can be concluded that the value of TIME will affect the wave heights calculated by this procedure, but the effect is small.

Realizing the limitations imposed by the initial assumptions of Putnam and Johnson and the calculating procedure employed here, the computer program was used to compute the wave height (with bottom friction included) for varying initial periods and bottom slopes. The results are shown in Table 5. (In arriving at these results it was assumed that the initial wave height was 5 feet and the friction coefficient was 0.01.) The reduction in wave height (in terms of percent of the wave height

TABLE III

WAVE HEIGHT REDUCTION DUE TO BOTTOM FRICTION AS DETERMINED BY PUTNAM

AND JOHNSON AND BY THE NUMERICAL WAVE REFRACTION PROGRAM.

T = 12 sec. H_o = 5 FT. f = .01 TIME = 30 sec.

Bottom slope = 1:300 Breaking depth = 11.5 Ft.

DISTANCE FROM WHERE h = Lo/2 TO BREAKING POINT	PERCENT REDUCTION WAVE HEIGHT	
	FARRELL CONSTANT DEPTH STEPS	PUTNAM & JOHNSON CONSTANT SLOPE
PCT	PCT	PCT
0.0	0.0	0.0
50.0	0.0	0.0
62.0	0.2	0.2
70.3	0.4	0.4
80.5	1.0	1.1
86.8	1.9	2.1
90.8	3.1	3.2
93.0	4.2	4.5
95.0	6.0	6.2
97.1	8.7	9.3
100.0	18.5	20.8

TABLE IV

PERCENT REDUCTION IN WAVE HEIGHT FOR VARIOUS VALUES OF TIME

TIME (SEC)	WAVE HT. REDUCTION (%)
20	19.0
30	18.5
40	18.0
50	17.0

TABLE V

WAVE HEIGHT REDUCTION FOR BOTTOM SLOPES OF 1:100 to 1:400 AND WAVE

PERIODS OF 8 to 16 SECONDS   (PERCENT)

WAVE PERIOD	BOTTOM SLOPE			
	1:100	1:200	1:300	1:400
8	5.4	14.0	21.5	28.6
10	5.2	13.5	20.2	27.0
12	5.2	13.0	18.5	24.8
16	5.0	12.2	18.2	24.2
AVERAGE	5.2	13.2	19.6	26.9

without friction) is shown for the theoretical breaking depth (from H.O. 234). To obtain the percent reduction at the specific breaking depth, it was necessary to fit a smooth curve to the plotted points of wave height reduction at the three closest water depths and interpolate the wave height reduction at the breaking point.

Figure 9 shows the average reduction (for all periods from Table 5) of wave height versus bottom slope. The curve is extended by a dashed line to the reduction amount found by Putnam and Johnson for a 1:10 beach slope.

The quantitative value of Figure 9 is controlled by the input accuracy of the coefficient of friction, the initial assumptions and the computation procedure. However, Figure 9 does show, qualitatively, the effect of bottom slope on wave height reduction due to bottom friction. Figure 9 is considered sufficiently accurate to be used in surf forecasting on sandy beaches to provide a first approximation of wave height reduction due to bottom friction.

Figure 9. EXPECTED WAVE HEIGHT REDUCTION AT BREAKING
POINT DUE TO BOTTOM FRICTION FOR BOTTOM SLOPES OF
1:10 to 1:400.
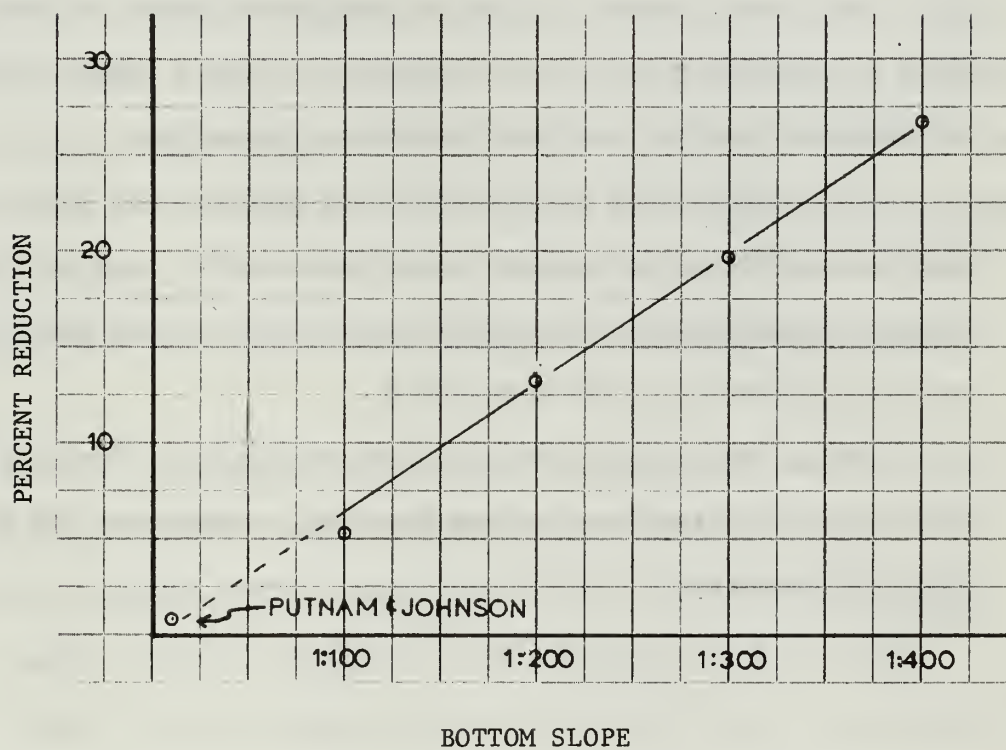
5. Conclusions.

The numerical approach to wave refraction is a powerful tool in that it eliminates human subjectivity and permits the refraction computations to account for more factors than is possible with hand drawn techniques.

A computer program that uses constant time intervals between computations has more suitability in accounting for the effects of friction, wind, reflection, etc., than a computer program that employs constant distance steps.

Tide level changes can have a significant effect on wave refraction. This is especially true in areas where there is a large tide range or an offshore bar that can cause selective refraction.

The changes shown by the tide level effects also point to the importance of having an accurate water depth grid. To avoid significant errors in the refraction pattern a great deal of care must be exercised in the preparation of the depth grid.

Bottom friction can and does have an effect on the wave height. The numerical refraction program provides a convenient way to account for this reduction.

6.   Recommendations.

The course of this investigation has permitted a close look at wave

refraction from many points of view. The numerical refraction program

is capable of yielding wave refraction information with great speed and

accuracy. (Computer time is approximately 5 minutes for a 20 ray diagram.)

However, before the advantages of the computer product can be fully

realized the author believes further investigations and improvements are

needed in the areas of input data, computing procedures and field in-

vestigations.

The need for accurate depth information is essential to the compu-

tation of accurate refraction patterns. It is anticipated that the present

efforts of the Naval Oceanographic Office and the Coast and Geodetic Survey

in the area of color photography will improve the water depth information

especially in areas where the bottom contours change considerably and

in the shallow areas where it is difficult for hydrographic vessels to

proceed.

The computer program can be expanded to account for more variables

and to provide additional output information; in particular:

(1) The program should account for the fact that in nature there

    usually exists a spectrum of wave periods and directions,

    rather than the single period and direction that is considered

    here.

(2) For amphibious operations it would be advantageous if the

    program determined the breaking depth of the waves, printed out

    the height of the waves at the breaking point, and then contoured

    the breaking point on the output refraction diagram.

(3) Another desirable output for amphibious operations is a computer plot on the output diagram of the area where the wave height is a minimum, as this would be an ideal area to anchor large ships.

(4) The various subroutines should be checked to ensure that each section is providing comparable accuracy.

Field work is necessary to determine the value of the bottom friction factor for various type bottoms. This is essential before accurate wave height information can be obtained. Field investigations are also needed to determine the accuracy of the computer program; until now the numerical wave refraction procedures have been checked only by comparison with hand drawn results.

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APPENDIX 1

Computer Program for Wave Refraction using Fortran 63

on the C.D.C. 1604 Computer

Subroutine Title: FRICT[1]

Variables of Subroutine:

HHQ............Height of wave at point X, Y after bottom friction
 has been included.

RLO............Deep water wave length.

RLQ............Wave length at point X, Y.

CFF............Friction factor between point n and n+1.

RCFF...........$(1 - K_f)$

TRCFF..........Total of $(1-K_f)$ terms to point n.

TCFF...........Total friction factor to point n.

Summary of Subroutine:

The subroutine calculates the value of K_f and wave height reduced

by bottom friction (HHFR) for each point along wave ray.

_____

[1]See Stouppe (1966) for discussion of remainder of program.

```
      PROGRAM WAVREFR                                                    0000000
C     REFRACTION IN SHOALING WATER BY LT. D. STOUPPE,OCTOBER 1966        00000010
C     WAVE REFRACTION PROGRAM FOR THE COMPUTATION OF CREST AND RAY       00000020
C     THE PROGRAM WAS MODIFIED BY LT. C. FARRELL ,MAY 1967, TO           00000030
C     INCLUDE THE EFFECT OF FRICTION AND TIDE LEVEL. THE PROGRAM IS      00000040
C     WRITTEN IN FORTRAN 63 FOR THE CDC 1604 COMPUTER SYSTEM.            00000050
C     USERS MAY ENTER THE DESIRED NAMES FOR THE GRAPH TITLES IN THE      00000060
C     ITITLE STATEMENTS AS DESCRIBED IN THE WRITEUP ON THE DRAW          00000070
      SUBROUTINE.                                                        0000008
      DIMENSION ITITLE(12),XXX(100),YYY(100),FX(100),FY(100)            00000090
      COMMON/BLK1/X(100),Y(100),COREFR(1  ),HHO(100),B(3,100),FFK(100),  00000100
     1NOGO(100),NGO,AAA(100)                                             0000011
      COMMON/BLK2/T,A,CXY,PAR,BAR,TIME,GRID,FK,MAX,NOR,MM,NN,DEPTH,HHA,   00000120
     1COREFA,NORA,LO,DIST                                                0000013
      COMMON/BLK3/DEP(100,100),PDPX,PDPY,PCPX,PCPY,PDDPXX,PDDPYY          00000140
     1,PDDPXY,PDDPCC,PDFC                                                00000150
      COMMON/BLK4/FFKK(100),DLO,C(6),MIT,DEL Y,DEL X,DEL Y,FCF,TIDE,HINT, 00000160
     1HHF,HHFR(100),LQQ,HHQ,DEPTH1                                       0000017
      READ 74,MM,NN                                                      0000018
   74 FORMAT(2I10)                                                       0000019
C     NOTE MM AND NN MUST BE RIGHT ADJUSTED                             00000200
      READ 1,((DEP(I,J),J=1,NN),I=1,MM)                                  0000021
    1 FORMAT   (14F5.0)                                                  0000022
  333 READ 2,XV,YV,FCF,TIDE,HINT,T,A1,NOR,TIME,DIST,GRID                 00000230
    2 FORMAT  (2F7.0,F5.2,4F5.1,I5,F5.1,2F7.0)                           00000240
      PRINT 19                                                           0000025
   19 FORMAT  (1H1,2X,2HXV,5X,2HYV,4X,3HFCF,1X,4HTIDE,1X,4HHINT,2X,      00000260
     1HT,4X,2HA1,2X,3HNOR,2X,4HTIME,2X,4HDIST,3X,4HGRID)                 00000270
      PRINT 2,XV,YV,FCF,TIDE,HINT,T,A1,NOR,TIME,DIST,GRID                00000280
      DO 516 I=1,MM     $     DO 516 J=1,NN                              0000029
      IF(DEP(I,J))501,516,502                                            0000030
  501 DEP(I,J)=DEP(I,J)*6.0-TIDE                                         0000031
      GO TO 516                                                          0000032
  502 DEP(I,J)=DEP(I,J)*6.0+TIDE                                         0000033
  516 CONTINUE                                                           0000034
      B1=1.0                                                             0000035
```

```
      B2=1.0                                                           0000036
      MAX=1 $ A1=A1*.01745329 $ PAR=32.2*T/6.283185 $ BAR=6.283185/T   00000370
      LQQ=1                                                            0000038
      NIP=4                                                            0000039
      IFG=TIDE     $    IAQ=A1     $     ITQ=T                          00000400
      LABEL=4H                                                         0000041
      DO 18 M=1,12                                                     0000042
   18 ITITLE(M)=8H       $ ITITLE(1)=8HFARRELL $ ITITLE(2)=8H WAVE RE  00000430
      ITITLE(3)=8HFRACTION $ ITITLE(4)=8H PROGRAM                      00000440
      ITITLE(5)=8H  MONTER                                             0000045
      ITITLE(6)=8H EY BAY                                              0000046
      ITITLE(7)=8HTIDE LVL                                             0000047
      ITITLE(8)=IBCD(IFG,0,4,IEQ)                                      0000048
      ITITLE(9)=8HANGLE =                                              0000049
      ITITLE(10)=IBCD(IAQ,0,4,IEQ)                                     00000050
      ITITLE(11)=8HPERIOD =                                            0000051
      ITITLE(12)=IBCD(ITQ,0,4,IEQ)                                     00000052
      B(1,1)=B1 $ B(2,1)=B2 $ XX=XV $ YY=YV $ NORA=1 $ A=A1            00000530
      IF(T-10.)15,16,17                                                0000054
   15 CXY= 30.0 $ GO TO 3                                              0000055
   16 CXY= 50.0 $ GO TO 3                                              0000056
   17 CXY=80.0 $ GO TO 3                                               0000057
    5 B(1,NORA)=B1 $ B(2,NORA)=B2 $ A=A1                               0000058
      XV=XV-DIST*SINF(A) $ YV= YV+DIST*COSF(A) $XX=XV $ YY=YV $ GO TO 3 00000590
   23 NORA=1                                                           0000060
   24 XX=X(NORA) $ YY=Y(NORA) $ A=AAA(NORA)                            00000610
    3 CALL RAYN(XX,YY,NOR)                                             0000062
      CONTINUE $ NORA=NORA+1 $ IF(NORA-NOR)10,10,4                     00000630
   10 IF(MAX-1)5,5,24                                                  0000064
    4 IF(MAX-1)20,20,25                                                0000065
   25 IF(NIP-4)21,26,26                                                0000066
   20 CALL DRAW(NOR,X,Y,1,2,LABEL,ITITLE,10000.,10000.,0.,0.,2.,2.,9.,9 ,1.,  00000670
     1LAST) $ GO TO 27                                                 0000068
   26 CALL DRAW(NOR,X,Y,2,2,LABEL,ITITLE,10000.,10000.,0.,0.,2.,2.,9.,9 ,1.,  00000690
     1LAST)                                                            0000070
   27 CALL DRAW(NOR,X,Y,2,0,LABEL,ITITLE,10000.,10000.,0.,0.,2.,2.,9.,9 ,1.,  00000710
```

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```
    1 LAST)
      NIP=1
   21 NIP=NIP+1 $ MAX=MAX+1 $ MIN=MAX-1                                        0000072
   33 DO 32 M=1,NOR $ FX(M)=X(M)/3. $ FY(M)=Y(M)/3.                           0000073
   32 CONTINUE                                                                0000074
   34 PRINT 28,MIN                                                            00000750
   28 FORMAT(//17HNUMBER OF CREST = I4/)                                      0000076
      PRINT 6                                                                 0000077
    6 FORMAT(/4X,1HX,9X,1HY,6X,6HCOREFA,3X,3HHHO,5X,4HHHFR,5X,5HDEPTH,        0000078
     11X,3HNGO,6X,1HX,7X,2HY,6X,6HCOREFA,3X,3HHHO,5X,4HHHFR,5X,5HDEPTH,       0000079
     21X,3HNGO)                                                              00000800
      DO 7 J=1,NOR,2                                                         00000810
      PRINT 8,FX(J),FY(J),COREFR(J),HHO(J),HHFR(J),DEPTH1(J),NOGO(J),        0000082
     1FX(J+1),FY(J+1),COREFR(J+1),HHO(J+1),HHFR(J+1),DEPTH1(J+1),            0000083
     2NOGO(J+1)                                                             00000840
    8 FORMAT(2(2F9.1,3F8.4,F9.1,I4)/)                                        00000850
    7 CONTINUE                                                                0000086
      DO 9 I=1,NOR $ DO 9 J=2,3                                               0000087
    9 B(J,1,I)=B(J,I) $ NNGO=0 $ DO11 K=1,NOR                                 0000088
      IF(NOGO(K)-1)12,12,11                                                   0000089
   12 NNGO=NNGO+1                                                            00000900
   11 CONTINUE $ IF(NNGO-NOR) 13,14,14                                        0000091
   13 GO TO 23                                                                0000092
   14 CONTINUE                                                                0000093
      M=1 $ DO31I=1,MM $ DO31J=1,NN $ IF(DEP(I,J))31,30,31                    0000094
   30 XXX(M)=(I-1)*GRID $ YYY(M)=(J-1)*GRID $ M=M+1 $ N=M-1                    0000095
   31 CONTINUE                                                               00000960
      CALL DRAW(N,XXX,YYY,3,0,LABEL,ITITLE,10000.,10000.,0,0,2,9,9 ,         00000970
     11,LAST)                                                                 0000098
      DO616 I=1,MM    $    DO616J=1,NN                                       00000990
      IF(DEP(I,J))601,616,602                                                 0000100
  601 DEP(I,J)=(DEP(I,J)+TIDE)/6.0                                            0000101
      GO TO 616                                                               0000102
  602 DEP(I,J)=(DEP(I,J)-TIDE)/6.0                                            0000103
  616 CONTINUE                                                                0000104
      GO TO 333                                                              0000105
                                                                             0000106
                                                                             0000107
```

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      END                                                              108
      SUBROUTINE RAYN(XX,YY,NOR)                                    0000109
      COMMON/BLK1/X(100),Y(100),COREFR(1   ),HHO(100),B(3,100),FFK(100),  00001100
     1NOGO(100),NGO,AAA(100)                                        0000111
      COMMON/BLK2/T,A,CXY,PAR,BAR,TIME,GRID,FK,MAX,ABC,MM,NN,DEPTH,HHA,  00001120
     1COREFA,NORA,LO,DIST                                           0000113
      COMMON/BLK3/DEP(100,100),PDPX,PDPY,PCPX,PCPY,PDDPXX,PDDPYY     00001140
     1,PDDPXY,PDDPCC,PDPC                                           0000115
      COMMON/BLK4/FFKK(100),DLO,C(6),MIT,DEL X,DEL Y,FCF,TIDE,HINT,  00001160
     1HHF,HHFR(100),LQQ,HHQ,DEPTH1                                  0000117
      IF(MAX-1)110,110,111                                          0000118
  110 NGO=2 $ GO TO 108                                             0000119
  111 NGO=NOGO(NORA) $ GO TO (104,108)NGO                           00001200
  108 CALL DEPTFUN(XX,YY)                                           0000121
      GO TO (104,102)NGO                                            0000122
  104 NGO=1                                                         0000123
      GOREFA=0.0                                                    0000124
      B(3,NORA)=0.0                                                 0000125
      FK= .0                                                        0000126
      HHA=0.0                                                       0000127
      HHF=0.0                                                       0000128
      GO TO 103                                                     0000129
  102 IF(MAX-1)105,105,107                                          0000130
  105 CALL KFUNCT(A,FK) $ GO TO 106                                 0000131
  107 FK=FFK(NORA)                                                  0000132
  106 CALL MOVE(XX,YY) $ GO TO(104,109)NGO                          00001330
  109 CALL BETA(XX,YY)                                              0000134
  103 FFK(NORA)=FK $ COREFR(NORA)=COREFA $ HHO(NORA)                00001350
     1=HHA $ NOGO(NORA)=NGO $ X(NORA)=XX $ Y(NORA)=YY $ AAA(NORA)=A  00001360
      DEPTH1(NORA)=DEPTH                                            0000137
      HHFR(NORA)=HHF                                                0000138
      RETURN                                                        0000139
      END                                                             140
      SUBROUTINE DEPTFUN(XX,YY)                                     0000141
      DIMENSION D(6,6),E(6),    O(100),P(100)                       00001420
      COMMON/BLK1/X(100),Y(100),COREFR(1   ),HHO(100),B(3,100),FFK(100),  00001430
```

```
      1NOGO(100),NGO,AAA(100)
      COMMON/BLK2/T,A,CXY,PAR,BAR,TIME,GRID,FK,MAX,NOR,MM,NN,DEPTH,HHA,        0000144
     1COREFA,NORA,LO,DIST                                                      00001450
      COMMON/BLK3/DEP(100,100),PDPX,PDPY,PCPX,PCPY,PDDPXX,PDDPYY               0000146
     1,PDDPXY,PDDPCC,PDPC                                                      00001470
      COMMON/BLK4/FFKK(100),DLO,C(6),MIT,DEL X,DEL Y,FCF,TIDE,HINT,            0000148
     1HHF,HHFR(100),LQQ,HHQ,DEPTH1                                             00001490
      XR=XX/GRID $ K=XR+1.5 $ YR=YY/GRID $ L=YR+1.5                            0000150
    7 IF((XX-1.0)*((MM-1)-K))62,7,7                                            00001510
      IF((YY-1.0)*((NN-1)-L))62,6,6                                            0000152
    6 DO9J=1,6 $ DO9I=1,6                                                      0000153
    9 D(I,J)=0.0 $ DO8 I=1,6                                                   0000154
    8 E(I)=0.0                                                                 0000155
      M=L $ MA=L+1 $ N=K-1 $ NA=K+1                                            0000156
      DO1   J=M,MA $ DO10 I=N,NA $ O(I)=(I-1)*GRID $ P(J)=(J-1)*GRID           0000157
      D(1,1)=9.$D(2,1)=D(2,1)+O(I)$D(3,1)=D(3,1)+P(J)$D(4,1)=D(4,1)+O(I        00001580
     1)*P(J)$D(5,1)=D(5,1)+O(I)**2$D(6,1)=D(6,1)+P(J)**2$E(1)=E(1)+DEP         00001590
     2(I,J)$D(1,2)=D(2,2)=D(5,1)$D(3,2)=D(4,1)$D(4,2)=D(4,2)+O(I               00001600
     3)**2*P(J)$D(5,2)=D(5,2)+O(I)**3$D(6,2)=D(6,2)+O(I)*P(J)**2$E(2)=         00001610
     4E(2)+O(I)*DEP(I,J)$D(1,3)=D(3,1)$D(2,3)=D(4,1)$D(3,3)=D(6,1)$D(4,        00001620
     53)=D(4,3)+O(I)*P(J)**2$D(5,3)=D(6,3)=D(4,1)$P(J)**3$E(3)=                00001630
     6E(3)+P(J)*DEP(I,J)$D(1,4)=D(4,1)$D(2,4)=D(4,2)$D(3,4)=D(6,2)$D(4,        00001640
     74)=D(4,4)+O(I)**2*P(J)**2$D(5,4)=D(5,4)+O(I)**3*P(J)$D(6,4)=D(6,4        00001650
     8)+O(I)*P(J)**3$E(4)=E(4)+O(I)*P(J)*DEP(I,J)$D(1,5)=D(5,1)$D(2,5)=        00001660
     9D(5,2)$D(3,5)=D(4,2)$D(4,5)=D(5,4)$D(5,5)=D(5,5)+O(I)**4$D(6,5)=         00001670
     1D(4,4)$E(5)=E(5)+O(I)**2*DEP(I,J)$D(1,6)=D(6,1)$D(2,6)=D(6,2)$D(3        00001680
     2,6)=D(6,3)$D(4,6)=D(6,4)$D(5,6)=D(4,4)$D(6,6)=D(6,6)+P(J)**4$E(6)        00001690
     3=E(6)+P(J)**2*DEP(I,J)                                                   00001700
   10 CONTINUE                                                                 0000171
      NPM=7 $ DO 34M=1,6 $ KP=0 $ Z=0.0 $ DO12N=M,6 $ IF(Z-ABSF(D(N,M)        0000172
     1))11,12,12                                                              00001730
   11 Z=ABSF(D(N,M)) $ KP=N                                                    0000174
   12 CONTINUE $ IF(M-KP)13,20,20                                              0000175
   13 DO14J=M,NPM $Z=D(M,J) $ D(M,J)=D(KP,J)                                   0000176
   14 D(KP,J)=Z                                                                00001770
   20 IF(ABSF(D(M,M))-.00001)50,50,30                                          0000178
                                                                              0000179
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30 IF(M-6)31,40,40                                                              0000180
31 LP1=M+1 $ DO34N=LP1,6 $ IF(D(N,M))32,34,32                                    00001810
32 RATIO=D(N,M)/D(M,M)$ DO33J=LP1,NPM                                            0000182
33 D(N,J)=D(N,J)-RATIO*D(M,J)                                                    0000183
34 CONTINUE                                                                      0000184
40 DO43I=1,6 $ II=7-I $              JPN=7    $ S=0.0 $ IF(II-6)41,43,           00001850
   143                                                                          186
41 IIP1=II+1 $ DO 42N=IIP1,6                                                     0000187
42 S=S D(II,N)*C(N)                                                             0000188
43 C(II)  =(D(II,JPN)-S)/D(II,II)  $ KER=1 $ GO TO 51                           00001890
50 KER=2                                                                        0000190
   PRINT 54,XX,YY,KER                                                           0000191
54 FORMAT(/3X,5HXX = 1PE20.8,3X,5HYY = 1PE20.8,4X,6HKER = I2,                   00001920
   117H MATRIX SINGULAR/)                                                       0000193
51 GO TO (52,53)KER                                                            0000194
53 RETURN                                                                       0000195
52 CONTINUE                                                                     0000196
   DEPTH=C(1)+C(2)*XX+C(3)*YY+C(4)*XX*YY+C(5)*XX**2+C(6)*YY**2                  00001970
   IF(DEPTH)62,62,65                                                           0000198
65 ALO=PAR*T $ DLO=DEPTH/ALO $ IF(DLO  .5)63,63,66                             00001990
66 CXY=PAR $ LO=1 $ NGO=2 $ FK=0. $ GO TO 67                                    00002000
63 DO6 M=1,50 $ CXX=PAR*TANHF(BAR*DEPTH/CXY)                                    00002010
   IF(ABSF(CXX-CXY)-0.01)61,61,60                                              0000202
60 CXY=(CXX+CXY)*.5                                                            0000203
61 CONTINUE  $ NGO=2 $ LO=2                                                    0000204
67 PDPX=C(2)+C(4)*YY+2*C(5)*XX                                                 0000205
   PDPY=C(3)+C(4)*XX+2*C(6)*YY                                                 0000206
   PDDPXY=C(4) $ PDDPXX=2*C(5) $ PDDPYY=2*C(6)                                 00002070
   GO TO 64                                                                     0000208
62 NGO=1                                                                       0000209
   GO TO 81                                                                     0000210
64 CONTINUE                                                                    0000211
81 RETURN                                                                      0000212
   END                                                                          213
   SUBROUTINE KFUNCT (A,FK)                                                    0000214
   COMMON/BLK1/X(100),Y(100),COREFR(1  ),HHO(100),B(3,100),FFK(100),          00002150
```

```
      1NOGO(100),NGO,AAA(100)                                                    0000216
      COMMON/BLK2/T,UU,CXY,PAR,BAR,TIME,GRID,VV,MAX,NOR,MM,NN,DEPTH,HHA           00002170
      1,COREFA,NORA,LO,DIST                                                       0000218
      COMMON/BLK3/DEP(100,100),PDPX,PDPY,PCPX,PCPY,PDDPXX,PDDPYY                   00002190
      1,PDDPXY,PDDPCC,PDPC                                                        0000220
    3 GO TO (5,6)LO                                                               0000221
    6 R1=CXY/32.2 $ R2=R1**3*BAR**2 $ R3=R1**5*BAR**4 $ R4=R1**7*BAR**6           00002220
      PDPC=2.*R1+4.*R2/3.+6.*R3/5.+8.*R4/7.                                       00002230
      PDDPCC=(2.*R1+4.*R2+6.*R3+8.*R4)/CXY                                        00002240
      PCPX=PDPX/PDPC $ PCPY=PDPY/PDPC                                             0000225
      FK=(PCPX*SINF(A)-PCPY*COSF(A))/CXY $ GO TO 4                                00002260
    5 FK=.                                                                        0000227
    4 RETURN                                                                      0000228
      END                                                                             229
      SUBROUTINE MOVE(X,Y)                                                        0000230
      COMMON/BLK1/U(100),V(100),COREFR(1  ),HHO(100),B(3,100),FFK(100),           00002310
      1NOGO(100),NGO,AAA(100)                                                     0000232
      COMMON/BLK2/T,A,CXY,PAR,BAR,TIME,GRID,FK,MAX,NOR,MM,NN,DEPTH,HHA,           00002330
      1COREFA,NORA,LO,DIST                                                        0000234
      COMMON/BLK3/DEP(100,100),PDPX,PDPY,PCPX,PCPY,PDDPXX,PDDPYY                   00002350
      1,PDDPXY,PDDPCC,PDPC                                                        0000236
      COMMON/BLK4/FFKK(100),DLO,C(6),MIT,DEL X,DEL Y,FCF,TIDE,HINT,               00002370
      1HHF,HHFR(100),LQQ,HHG,DEPTH1                                               0000238
      FKBAR=FFKK(NORA)                                                            0000239
      IF(MAX-1)1,1,4                                                              0000240
    1 FKBAR=FK                                                                    0000241
    4 MIT=1                                                                       0000242
      DEL D=TIME*CXY                                                              0000243
      GO TO (22,21)LO                                                            0000244
   22 XX=X+DELD*COSF(A) $ YY=Y+DELD*SINF(A) $ AA=A $ FKK=0. $ FKBAR=0.            00002450
      GO TO 6                                                                     0000246
   21 DO 20IT=1,30                                                               0000247
   19 DEL A=FKBAR*DEL D $ AA=A+DEL A $ ABAR=A+.5*DEL A $ DEL X=DEL D*             00002480
      1 COSF(ABAR) $ DEL Y=DEL D*SINF(ABAR) $ XX=X+DEL X $ YY=Y+DEL Y             00002490
      GO TO (101,6)MIT                                                            0000250
  101 CALL DEPTFUN(XX,YY)       $ GO TO(38,10)NGO                                 00002510
```

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10 CALL KFUNCT(AA,FKK) $ FKBAR=.5*(FK FKK)           00002520
   IF(IT-13)5,37,9                                   0000253
37 FKKPP=FKBAR                                        0000254
5  IF(MAX-1)7,7,9                                     0000255
7  IF(IT-1)20,20,9                                    0000256
9  IF(ABSF(FKKP-FKBAR)-.00001)6,6,20                  0000257
20 FKKP=FKBAR                                         0000258
24 IF(ABSF(FKKPP-FKBAR)-.00001)18,18,17               00002590
17 MIT=3    $NGO=1                                    0000260
   GO TO 38                                           0000261
18 FKBAR=.5*(FKBAR+FKKP) $ MIT=2 $ GO TO 19           00002620
6  NGO=2 $ GO TO 8                                    0000263
8  X=XX $ Y=YY $ A=AA $ FK=FKK                        0000264
38 CONTINUE                                           0000265
   FFKK(NORA)=FKBAR                                   0000266
   RETURN                                             0000267
   END                                                268
   SUBROUTINE BETA(XX,YY)                             0000269
   COMMON/BLK1/X(100),Y(100),COREFR(1   ),HHO(100),B(3,100),FFK(100),   00002700
  1NGO(100),NGO,AAA(100)                              0000271
   COMMON/BLK2/T,A,CXY,PAR,BAR,TIME,GRID,FK,MAX,NOR,MM,NN,DEPTH,HHA,   00002720
  1COREFA,NORA,LO,DIST                                0000273
   COMMON/BLK3/DEP(100,100),PDPX,PDPY,PCPX,PCPY,PDDPXX,PDDPYY   00002740
  1,PDDPXY,PDDPCC,PDPC                                0000275
   COMMON/BLK4/FFKK(100),DLO,C(6),MIT,DEL X,DEL Y,FCF,TIDE,HINT,   00002760
  1HHF,HHFR(100),LQQ,HHQ,DEPTH1                       0000277
   GO TO (5,6)LO                                      0000278
5  COREFA=1. $ HHA=1. $ B(3,NORA)=B(2,NORA) $ COREFB=1. $ HHB=1.   00002790
   HHF=1.0                                            0000280
   GO TO 7                                            0000281
6  PCCPXX=PDDPXX/(PDPC+PDDPCC)                        0000282
   PCCPYY=PDDPYY/(PDPC+PDDPCC)                        0000283
   PCCPXY=PDDPXY/(PDPC+PDDPCC)                        0000284
   P=( COSF(A)*PCPX-SINF(A)*PCPY)/CXY  $ Q=(SINF(A)**2*PCCPXX-2.*   00002850
  1SINF(A)*COSF(A)*PCCPXY+COSF(A)**2*PCCPYY)/CXY       00002860
   DD=SQRTF((DEL X)**2+(DEL Y)**2)                    0000287
```

50

```
      B(3,NORA)=(B(1,NORA)*(P*DD-2.)+B(2,NORA)*(4.-2.*DD**2*Q))        00002880
     1/(2.+P*DD)                                                       0000289
      COREFA=1./SQRTF(ABSF(B(2,NORA)))                                 0000290
      CCO=CXY/PAR $ HSHOL=3.2519-12.8150*CCO+28.8112*CCO**2-29.9257*CCO 00002910
     1**3 11.6815*CCO**4 $ HHA=COREFA * HSHOL                          00002920
      CALL FRICT (HHA,CXY,TIME,DEPTH,LQQ,PAR,T,HHF,NORA,NOR,           00002930
     1FCF,HINT,HSHOL)                                                  0000294
    7 RETURN                                                           0000295
      END                                                             296
      SUBROUTINE  FRICT(HHA,CXY,TIME,DEPTH,LQQ,PAR,T,HHF,NORA,NOR,     00002970
     1FCF,HINT,HSHOL)                                                  0000298
      DIMENSION  TCFF(100),TRCFF(100)                                  0000299
    1 CCO=CXY/PAR                                                      0000300
      DEL D=TIME*CXY                                                   0000301
      IF(LQQ-1)715,701,715                                             0000302
  701 DO 8  I=1,NOR                                                    0000303
      TCFF(I)=1.0                                                      0000304
      TCFF(I)=1.0                                                      0000305
      TRCFF(I)=0.0                                                     0000306
    8 CONTINUE                                                         0000307
      TFP=T**4                                                         0000308
  715 THET1=64.0*(3.141592**3)/(3.0*(32.2**2))                         00003090
      HHQ=HHA*HINT*TCFF(NORA)                                          0000310
      RLO=PAR*T                                                        0000311
      RLQ=RLO*CCO                                                      0000312
      APR=FCF*HHQ/TFP                                                  0000313
      THET2=SINHF(6.28315*DEPTH/RLQ)                                   0000314
      THETA=THET1*((HSHOL/THET2)**3)                                   0000315
      CFF=1.0/((APR*THETA*DEL D/HSHOL)+1.)                             00003160
      RCFF=1.-CFF                                                      0000317
      TRCFF(NORA)=TRCFF(NORA)+RCFF                                     0000318
      TCFF(NORA)=1.-TRCFF(NORA)                                        0000319
      HHF=HHQ/HINT                                                     0000320
      LQQ=5                                                            0000321
      RETURN                                                           0000322
      END                                                             323
```

```
        IDENT   SINHF                                   SINHF001
        SYSTEM                                          SINHF.002
        ENTRY   SINHF                                   SINHF003
EXP     DEC     709.089                                 SINHF004
EXP1    DEC     -709.78                                 SINHF005
EXP2    OCT     20005427102277575                       SINHF006
EXP3    OCT     20444000000002000                       SINHF007
EXP4    OCT     20025612507331225                       SINHF008
EXP5    OCT     17734335463440024                       SINHF009
EXP6    OCT     20037045606770111                       SINHF01
EXP7    OCT     20075356205606566                       SINHF011
EXP8    OCT     -0                                      SINHF012
ONE     DEC     1.0                                     SINHF013
HALF    DEC     0.5                                     SINHF014
SINHF   SLJ     **                                      SINHF015
        SIU   1 SINH3                                   SINHF016
        LIU   1 SINHF                                   SINHF017
        LDA   1 0                                       SINHF018
        ARS     24                                      SINHF019
        SAU     SINH1    STORE ARGUMENT                 SINHF020
        INI   1 1                                       SINHF021
        SIL   1 SINH3    STORE RETURN ADDRESS           SINHF022
SINH1   LDA     **                                      SINHF023
        AJP     SINH3    EXIT IF ZERO                   SINHF024
        THS     EXP      CHECK MAXIMUM X                SINHF025
        SLJ     ERROR1                                  SINHF026
        THS     EXP1     CHECK MINIMUM X                SINHF027
        SLJ     *+2                                     SINHF028
        SLJ     ERROR1                                  SINHF029
        FDV     EXP2                                    SINHF03
      + STA     =STEMP                                  SINHF031
        FSB     EXP3                                    SINHF032
        SAL     SINH2                                   SINHF033
        FAD     EXP3                                    SINHF034
        FSB     TEMP                                    SINHF035
        STA     TEMP                                    SINHF036
```

52

```
        FMU      TEMP                    SINHF037
        STA      =STEMP1                 SINHF038
        FAD      EXP7                    SINHF039
        STA      =STEMP2                 SINHF04
        LDA      EXP6                    SINHF041
        FDV      TEMP2                   SINHF042
        FAD      EXP5                    SINHF043
        FMU      TEMP1                   SINHF044
        FAD      EXP4                    SINHF045
        STA      TEMP2                   SINHF046
        FAD      TEMP                    SINHF047
        STA      TEMP1                   SINHF048
        LDA      TEMP2                   SINHF049
        FSB      TEMP                    SINHF05
        FDV      TEMP1                   SINHF051
SINH2   LRS      36                      SINHF052
        INA      **                      SINHF053
        AJP   2  *+1                     SINHF054
        INA      -1                      SINHF055
        INA      2000B                   SINHF056
        LLS      36                      SINHF057
        AJP   3  ERROR1                  SINHF058
        STA      TEMP                    SINHF059
        LDA      ONE                     SINHF06
        FDV      TEMP                    SINHF061
        SCM      EXP8                    SINHF062
        FAD      TEMP                    SINHF063
        FMU      HALF                    SINHF064
        SLJ      SINH3                   SINHF065
SINH3   ENI   1  **                      SINHF066
        SLJ      **                      SINHF067
ERROR1  LDQ      ERROR2                  SINHF068
        CALL     Q8QIBJOB                SINHF069
        BCD      1SINH OUT               SINHF07
        CALL     Q8QEXITS                SINHF071
ERROR2  51    6  14567B                  SINHF072
```

```
      65      SINHF                                     SINHF073
         END                                           SINHF074
      FUNCTION IBCD(NX,JT,NJ,IER)                       00000
      DIMENSION NN(8),NNT(8)                            00001
      NT=XABSF(NX)                                      00002
      IER=0  $  NEG=0   $   BLANK=20B                   00003
      NP=XMODF(NJ,8)                                    00004
      IF(JT.EQ.0) 51,52                                 00005
   52 IF(JT.EQ.1) 51,53                                 00006
   53 IER=2  $  IBCD=2020202020202020B  $  GO TO 60     000070
C  CHECK IF INPUT IS MORE THAN EIGHT PLACES             000080
   51 IF(NX) 5,6,7                                      00009
    7 NEG=1                                             00010
      IF(NX.GT.99999999) 10,17                          00011
   10 NT=99999999                                       00012
      IER=1                                             00013
      GO TO 17                                          00014
    5 IF(NX.LT.-9999999) 12,17                          00015
   12 NT= 9999999                                       00016
      IER=-1                                            00017
   17 FTEN=NT                                           00018
      DO 1 I=1,8                                        00019
      J=9 I                                             00020
      NN(J)=MODF(FTEN,10.)                              00021
    1 FTEN=INTF(FTEN/10.)                               00022
      GO TO 25                                          00023
C  IF INPUT IS ZERO SET ALL BLANK EXCEPT NN(8)=0        000240
    6 DO 40 I=1,7                                       00025
   40 NN(I)=BLANK                                       00026
      NN(8)=12B                                         00027
      JBL=7                                             00028
      GO TO 21                                          00029
   25 DO 3 I=1,8                                        00030
      IF(NN(I).EQ.0) 4,8                                00031
    4 NN(I)=BLANK                                       00032
    3 CONTINUE                                          00033
```

—

```
 8    JBL=I-1                                           00034
      DO 41 KK=I,8                                      00035
      IF(NN(KK).EQ.0) 42,41                             00036
42    NN(KK)=12B                                        00037
41    CONTINUE                                          00038
      IF(NEG.EQ.0) 20,21                                00039
20    NN(JBL)=40B $  JBL=JBL-1                           00040
21    IF(NP-JBL)26,26,27                                00041
27    NP=                                                  42
26    IF(JT.EQ.0) 30,31                                 00043
30    KJ=NP  $  GO TO 32                                00044
31    KJ=JBL-NP                                         00045
32    NK=KJ+1                                           00046
      DO 33 K=NK,8                                      00047
33    NNT(K-KJ)=NN(K)                                   00048
      DO 34 K=1,KJ                                      00049
34    NNT(K+8-KJ)=NN(K)                                 00050
      ENCODE(8,50,IBCD)  (NNT(I),I=1,8)                 00051
50    FORMAT(8R1)                                       00052
60    END                                                  53
      END
```

APPENDIX 2

Sample Computer Input and Output

Sample Input

52   56

```
440.  460.  515.  505.  510.  470.  425.  355.  300.  330.  370.  360.
340.  345.  350.  365.  375.  390.  455.  560.  700.  850.  950.  865.
550.  490.  470.  460.  415.  380.  335.  400.  460.  520.  560.  595.
510.  460.  400.  315.  275.  300.  220.  140.   80.   55.   53.   51.
360.  405.  450.  435.  445.  380.  330.  270.  235.  250.  280.  280.
290.  297.  300.  305.  315.  360.  420.  490.  655.  810.  930.  870.
540.  500.  515.  515.  480.  445.  440.  500.  540.  593.  630.  630.
610.  560.  515.  400.  315.  275.  234.  190.  110.   63.   53.   50.
295.  370.  370.  325.  325.  307.  260.  190.  170.  175.  190.  190.
240.  250.  250.  265.  275.  305.  405.  470.  570.  750.  900.  885.
560.  540.  550.  560.  550.  540.  550.  605.  620.  640.  610.  570.
540.  590.  570.  430.  300.  310.  280.  240.  170.   70.   55.   50.
240.  250.  235.  195.  225.  200.  190.  160.  130.  140.  160.  170.
190.  195.  210.  230.  250.  280.  350.  427.  490.  670.  820.  860.
610.  590.  590.  615.  600.  610.  620.  660.  650.  620.  560.  505.
480.  520.  560.  515.  405.  370.  320.  260.  190.   80.   60.   49.
150.  195.  200.  110.  125.  120.  115.   95.   80.   98.  105.  110.
162.  170.  180.  205.  210.  210.  290.  380.  455.  580.  740.  785.
660.  650.  640.  660.  660.  670.  690.  685.  650.  585.  510.  480.  ·
450.  490.  550.  525.  450.  380.  325.  270.  215.  120.   65.   50.
80.   80.   90.   75.   73.   70.   72.   70.   70.   70.   72.   80.
110.  120.  140.  160.  175.  195.  240.  290.  390.  475.  610.  670.
760.  720.  715.  725.  730.  710.  680.  655.  620.  540.  480.  445.  ·
440.  410.  550.  490.  415.  370.  325.  285.  235.  170.   85.   65.
61.   60.   60.   58.   60.   60.   61.   63.   60.   60.   65.   65.
80.   85.  100.  120.  130.  120.  160.  230.  280.  380.  460.  540.
770.  750.  735.  715.  665.  635.  620.  610.  570.  485.  440.  415.
425.  490.  550.  500.  445.  375.  315.  295.  245.  190.  110.   80.
47.   47.   48.   49.   52.   54.   53.   54.   56.   59.   60.   60.
63.   65.   70.   77.   82.   85.  110.  150.  185.  250.  340.  395.
560.  610.  590.  600.  570.  540.  525.  520.  500.  460.  410.  380.
420.  510.  515.  500.  465.  410.  283.  265.  235.  210.  145.  105.
```

```
4500. 2      .   .01  0.   5.0 18.0 10.0   10 30.0 1500.0 1500.0
4500. 2      .   .01  6.   5.0 18.0 10.0   10 30.0 1500.0 1500.0
```

SAMPLE COMPUTER OUTPUT

XV	YV	FCF	TIDE	HINT	T	AI	NOR	TIME	DIST	GRID
4500	20000	.1	5.0	18.0	10.	10	10	33.5	1500	1500

NUMBER OF CREST = 1

X	Y	COREFA	HHO	HHFR	DEPTH	NGO	X	Y	COREFA	HH	HHFR	DEPTH	NGO
2408.4	6826.0	1.0000	1.0000	1.0000	1112.9	2	2321.6	7319.3	1.000	1.0000	1.000	1229.3	2
2234.8	7811.7	1.0000	1.0000	1.0000	1288.8	2	2148.0	8334.1	1.000	1.0000	1.000	1413.1	2
2061.2	8796.5	1.0000	1.0000	1.0000	1537.5	2	1974.3	9288.9	1.000	1.0000	1.000	1659.9	2
1887.5	9781.3	1.0000	1.0000	1.0000	1984.2	2	1800.7	10273.7	1.000	1.0000	1.000	2514.5	2
1713.9	10766.1	1.0000	1.0000	1.0000	3051.2	2	1627.0	11253.5	1.000	1.0000	1.000	3891.5	2

NUMBER OF CREST = 2

X	Y	COREFA	HHO	HHFR	DEPTH	NGO	X	Y	COREFA	HH	HHFR	DEPTH	NGO
3309.2	6972.2	1.0000	.9195	.9195	405.2	2	3225.7	7478.7	1.0000	.9316	.9316	443.	2
3143.2	7971.0	1.0000	1.0000	1.0000	943.6	2	3056.4	8464.2	1.000	1.0000	1.000	1396.7	2
2969.6	8956.6	1.0000	1.0000	1.0000	1181.9	2	2882.8	9449.1	1.000	1.0000	1.000	1258.6	2
2796.0	9941.5	1.0000	1.0000	1.0000	1637.4	2	2709.1	10433.9	1.000	1.0000	1.000	2165.4	2
2622.3	10926.3	1.0000	1.0000	1.0000	2594.4	2	2535.5	11418.7	1.000	1.0000	1.000	3411.9	2

NUMBER OF CREST = 3

X	Y	COREFA	HHO	HHFR	DEPTH	NGO	X	Y	COREFA	HH	HHFR	DEPTH	NGO
4158.6	7085.7	1.0156	.9203	.9061	359.4	2	4087.5	7644.8	1.838	.9846	0	368.1	2
4027.3	8117.6	1.0000	.9129	.9129	383.7	2	3954.7	8622.6	1.000	.9214	.9214	411.3	2
3872.6	9115.9	1.0000	.9293	.9293	435.9	2	3792.6	9577.9	1.000	.9396	.9396	468.5	2
3704.4	10101.6	1.0000	1.0000	1.0000	1117.0	2	3617.6	10594.0	1.000	1.0000	1.000	1578.3	2
3530.8	11086.4	1.0000	1.0000	1.0000	2050.3	2	3443.9	11578.9	1.000	1.0000	1.000	2752.	2

NUMBER OF CREST = 4

X	Y	COREFA	HHO	HHFR	DEPTH	NGO	X	Y	COREFA	HH	HHFR	DEPTH	NGO
4988.6	7180.2	1.0415	.9413	.9179	350.2	2	4924.0	7678.5	1.2019	1.0885	0	357.4	2
4866.2	8237.5	1.0222	.9273	0	363.2	2	4807.7	8762.2	1.000	.9093	0	370.	2
4729.3	9258.8	.9928	.9012	0	365.6	2	4669.1	9643.9	1.138	1.038	0	371.4	2
4596.8	10242.5	1.0000	.9170	.9170	397.4	2	4526.0	10754.2	1.000	1.000	1.000	854.8	2
4439.2	11246.6	1.0000	1.0000	1.0000	1124.6	2	4352.4	11739.0	1.000	1.0000	1.000	1685.6	2
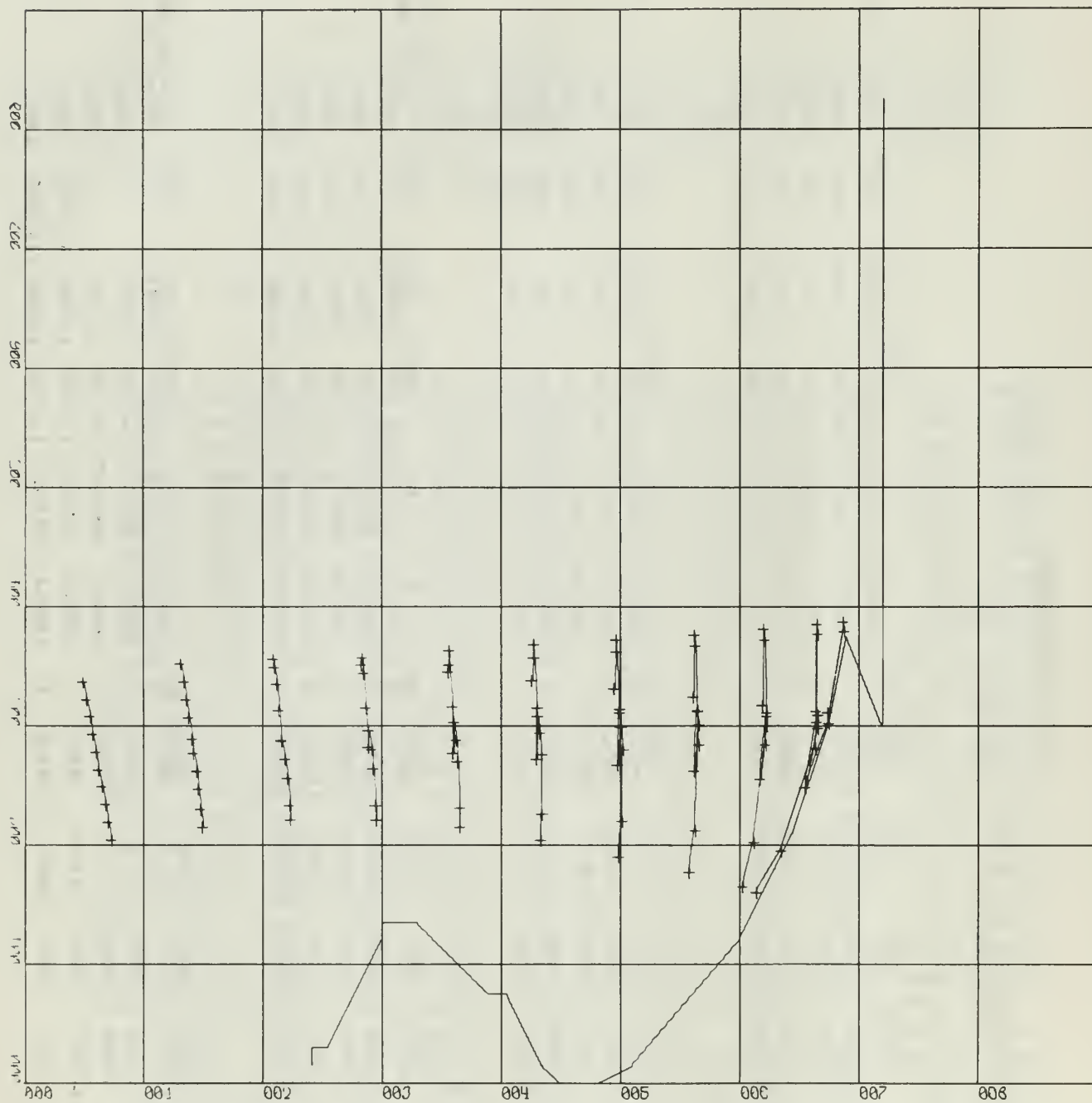
K-SCALE = 1.00E+04 UNITS/INCH.
Y-SCALE = 1.00E+04 UNITS/INCH.

FARRELL   WAVE REFRACTION PROGRAM MONTEREY BAY
TIDE LVL   0   ANGLE =   0   PERIOD = 18

SUMMARY OF EQUATIONS

Wave Speed (C)

$$C = \frac{gT}{2\pi} \tanh\left(\frac{2\pi d}{TC}\right).$$

Ray Curvature (FK)

$$FK = \frac{1}{C}\left[\sin A \frac{\partial c}{\partial x} - \cos A \frac{\partial c}{\partial y}\right].$$

Coefficient of Refraction (K_r)

The value of ray separation (β) is calculated by solving the second order, non-linear differential equation:

$$\frac{D^2\beta}{Ds^2} + P\frac{D\beta}{DS} + q\beta = 0$$

where

$$P = -\cos A \frac{1}{C}\frac{\partial c}{\partial x} - \sin A \frac{1}{C}\frac{\partial c}{\partial y}$$

$$q = \sin^2 A \frac{1}{C}\frac{\partial^2 c}{\partial x^2} - 2\sin A \cos A \frac{1}{C}\frac{\partial^2 c}{\partial x \partial y} + \cos^2 A \frac{1}{C}\frac{\partial^2 c}{\partial y^2}.$$

The above equation is solved by the finite difference method. This results in an equation for the Beta value at the n+1 point in terms of the Beta values at the two previous points. The equation to be solved is then:

$$\beta_3 = \frac{(pD - 2)\beta_1 + (4 - 2qD^2)\beta_2}{2 + pD};$$

where

D is the incremented distance

p,q are as defined above

β_1, β_2 are the Beta values of the two previous points. The The coefficient of refraction is calculated by the relation:

$$K_r = \sqrt{1/\beta}.$$

Direct Shoaling Coefficient (K_S):

$$H_s = 3.2519 - 12.8150 \left(\frac{c}{c_0}\right) + 28.8112 \left(\frac{c}{c_0}\right)^2 - 29.9257 \left(\frac{c}{c_0}\right)^3$$
$$+ 11.6815 \left(\frac{c}{c_0}\right)^4 .$$

Wave Height Reduction Factor Due to Bottom Friction (K_f):

$$K_f = \frac{1}{\dfrac{A' \phi_f}{K_S} \Delta \mathcal{H} + 1} ,$$

where

$$A' = \frac{f H_1}{T^4}$$

$$\phi_f = \frac{64 \pi^3}{3 g^2} \left(\frac{K_S}{\sinh \frac{2 \pi d}{L}}\right)^3 .$$

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11. SUPPLEMENTARY NOTES	**12. SPONSORING MILITARY ACTIVITY** Naval Postgraduate School Monterey, California

13. ABSTRACT

    Numerical wave refraction programs permit a detailed study of the transformation of wave energy as waves move from deep water to shallow water. By eliminating the subjectivity that is present with hand drawn diagrams the effect of small variations in the initial assumptions and wave conditions can be investigated. The effects on wave refraction of tide level changes and bottom friction are investigated here. It is demonstrated that a uniform increase in water level as would be caused by tidal fluctuations can cause a significant change in the wave refraction pattern for a given nearshore region. A computing procedure is developed to permit numerical refraction programs to account for bottom friction. The reduction in wave height caused by bottom friction depends primarily on bottom slope; this relation is shown in tabular and graphical form.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Wave Refraction						
Numerical Analysis						
Bottom Friction						
Tide level Changes						

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